The Swampland program in String Theory

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What is swampland?

For a normal person…

For a string theorist…

Whatever does not belong to string theory

For a phenomenologist…

New out-of-the-blue constraints to take care of

Not everything is possible in string theory/quantum gravity!!!

Swampland:

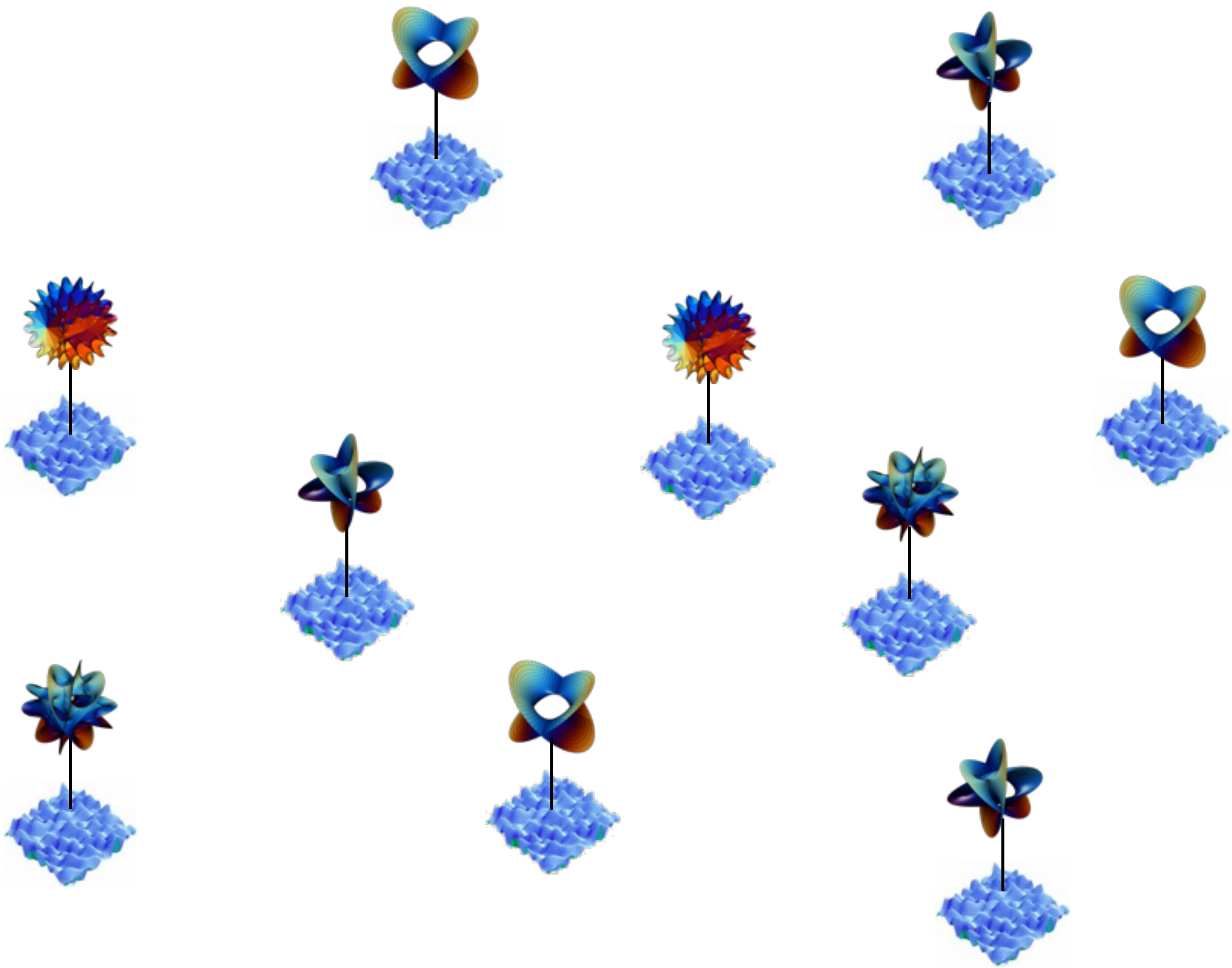
Apparently consistent (anomaly-free) quantum effective field theories that cannot be UV embedded in quantum gravity

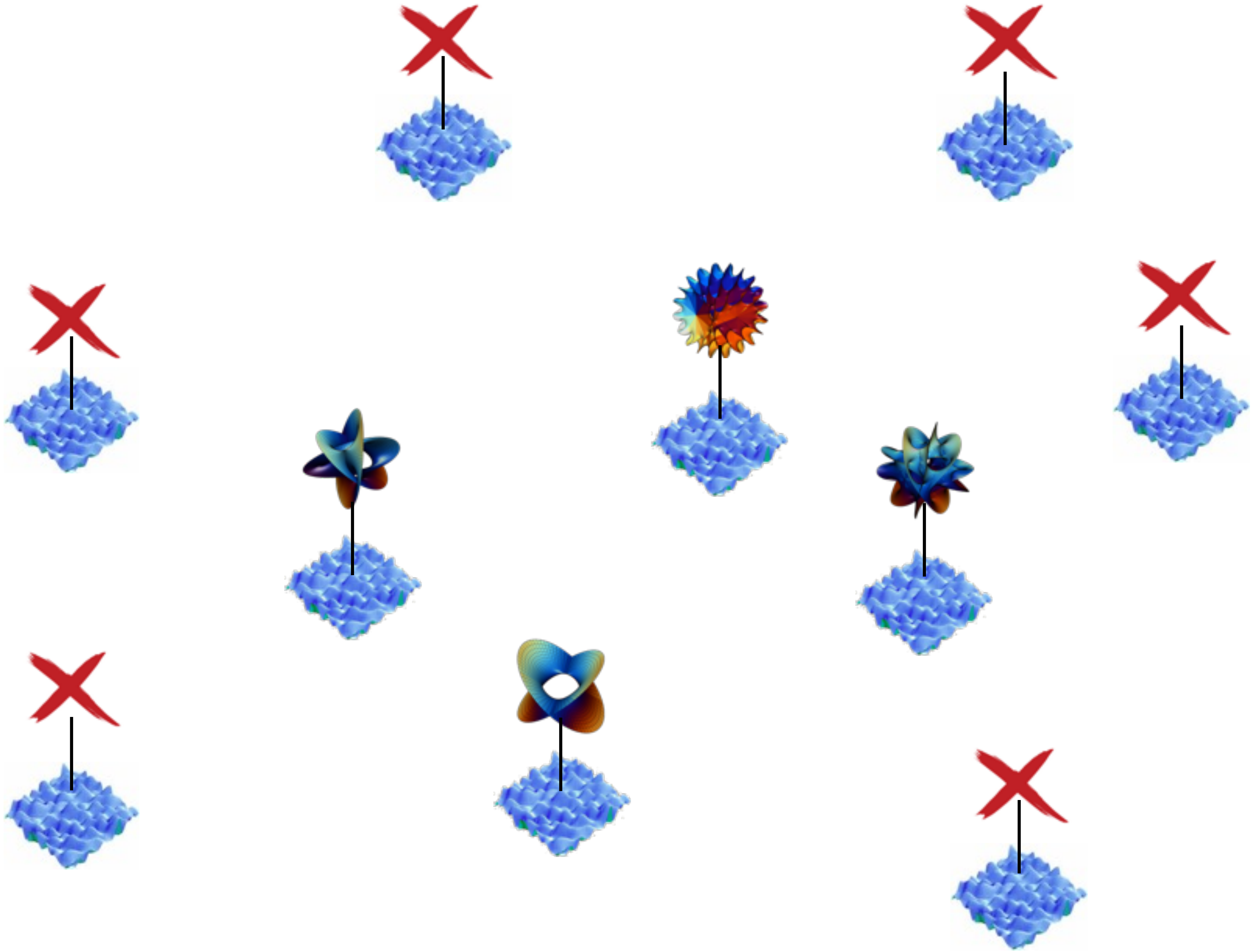
Not everything is possible in string theory/quantum gravity!!!

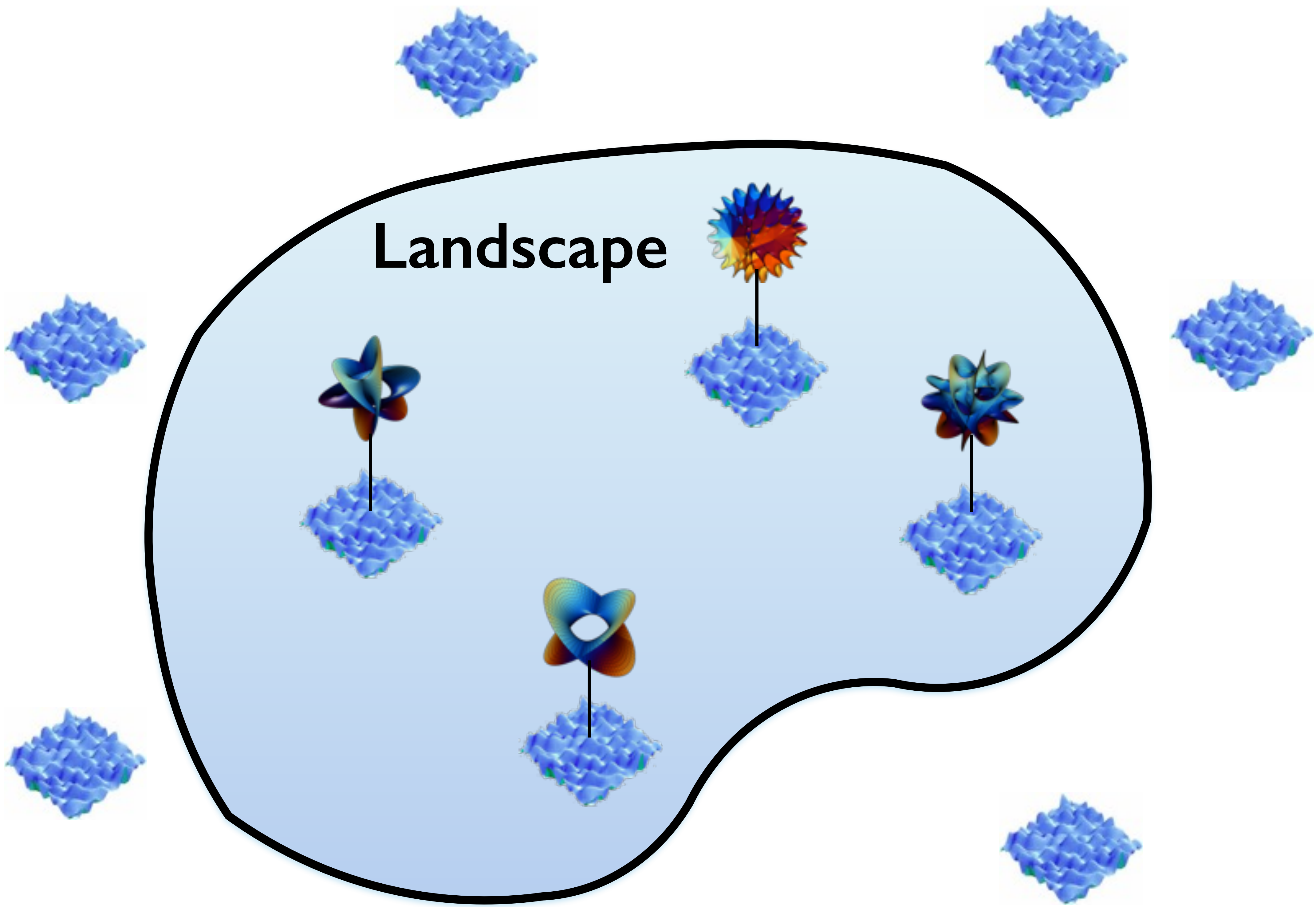
(String) **Swampland:**

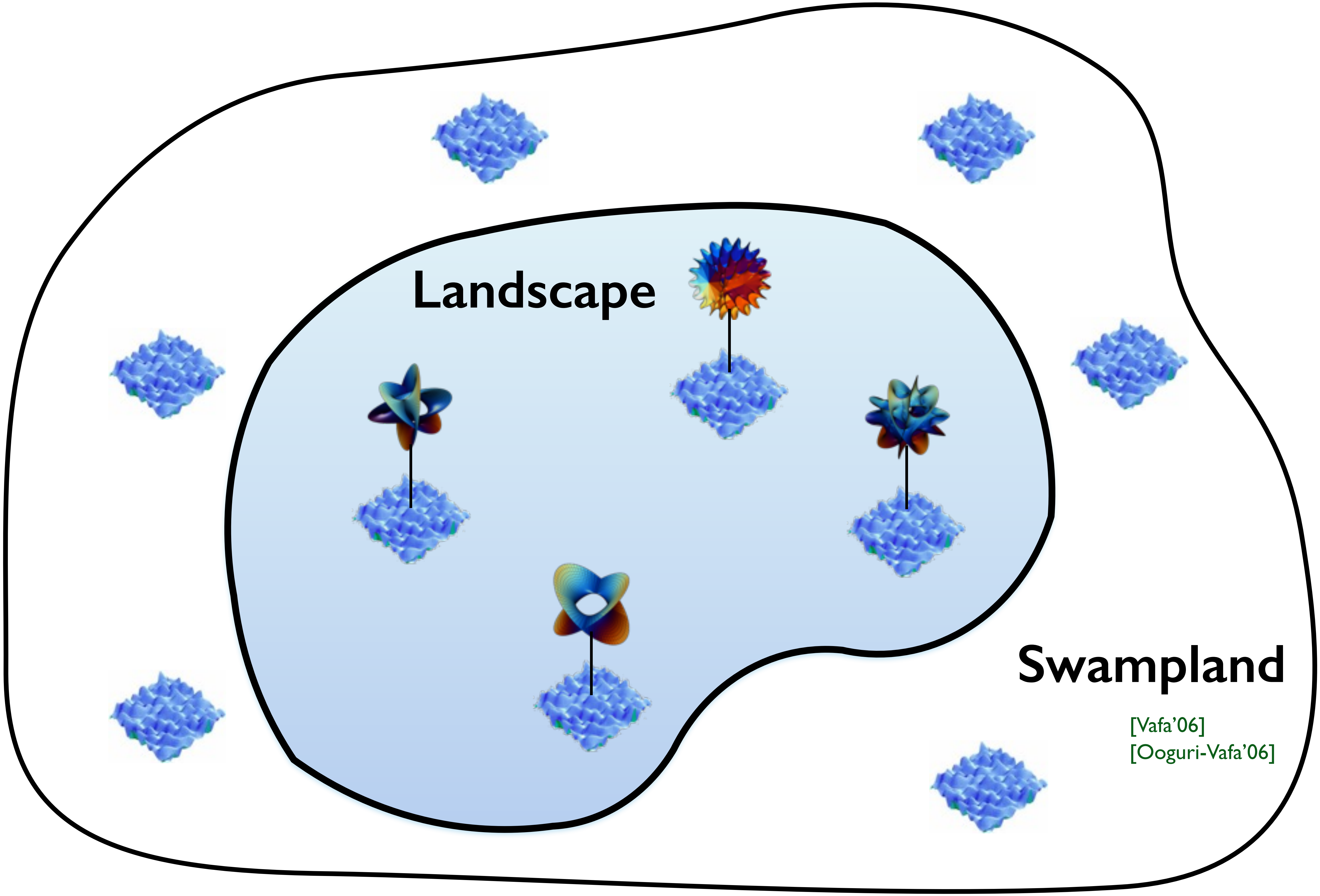
Apparently consistent (anomaly-free) quantum effective field theories that cannot be UV embedded in quantum gravity

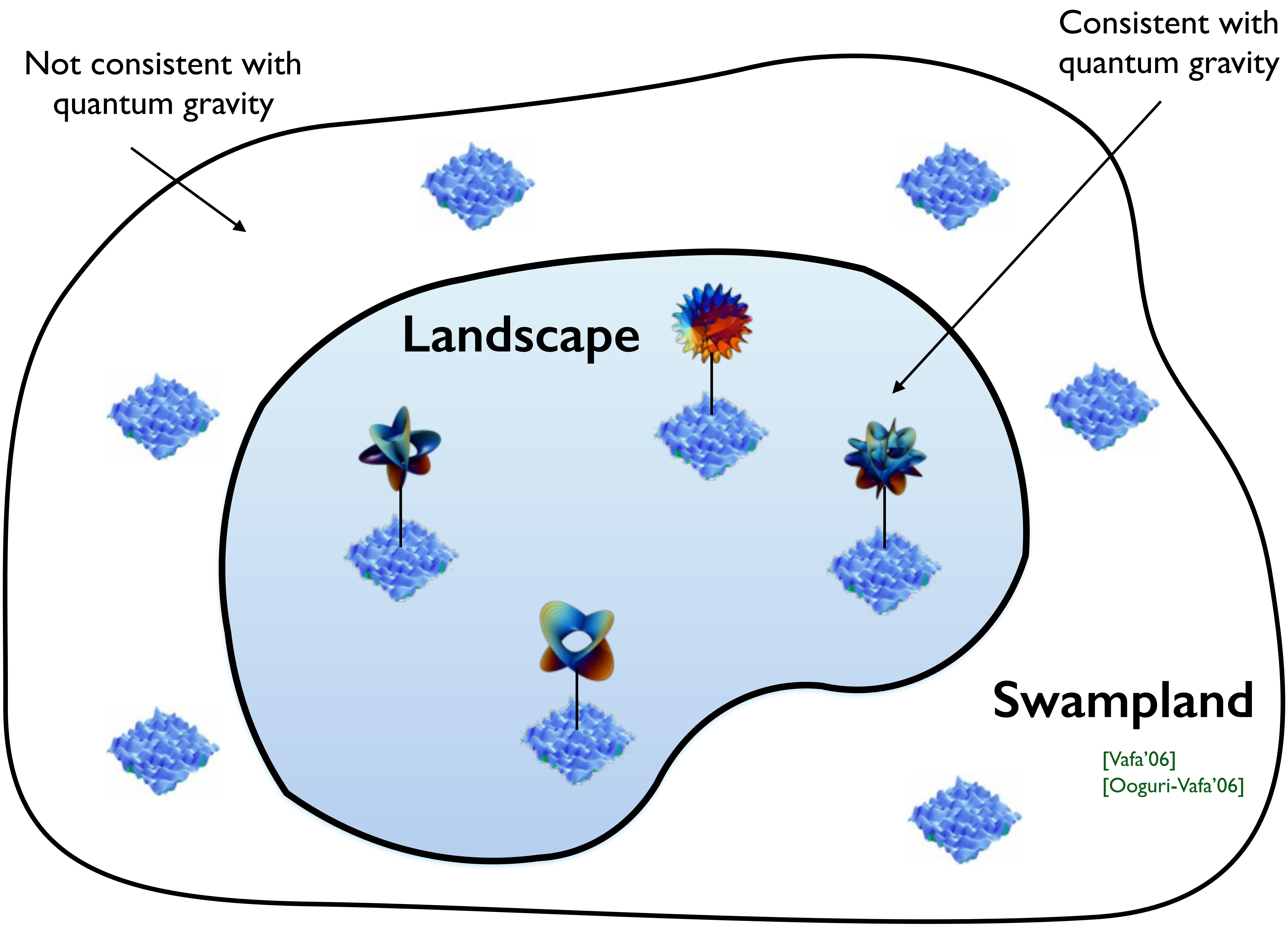
(they cannot arise from string theory)






Landscape


Landscape
Swampland
[Vafa'06]
[Ooguri-Vafa'06]


Not consistent with
quantum gravity
Consistent with
quantum gravity
Landscape
Swampland
[Vafa'06]
[Ooguri-Vafa'06]

What are the constraints that an effective theory must satisfy to be consistent with quantum gravity?

What distinguishes the landscape from the swampland?

First guess: Anomalies

QFT of scalars
and fermions

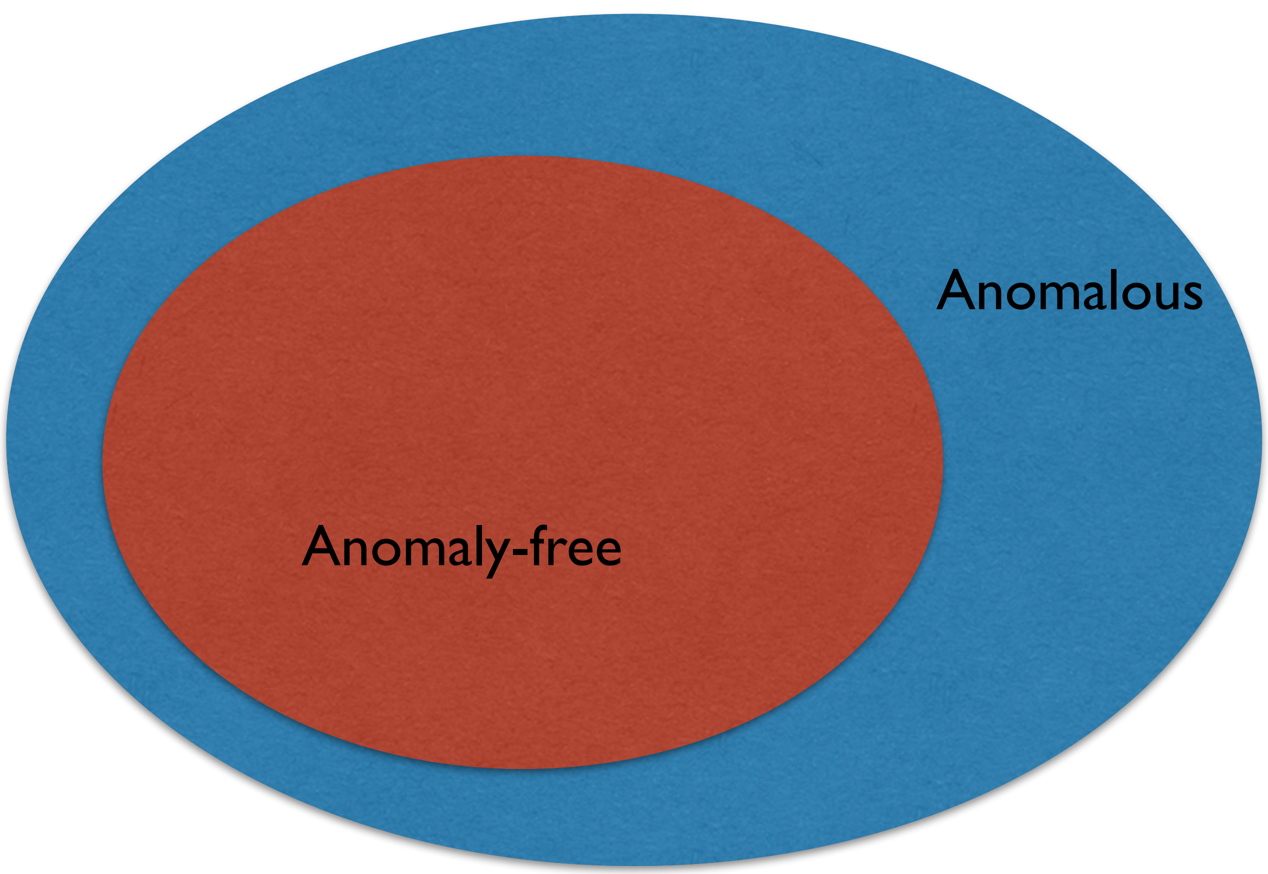
First guess: Anomalies

QFT of scalars
and fermions

→

QFT of scalars
and fermions
+ gauge fields

Anomaly
constraints



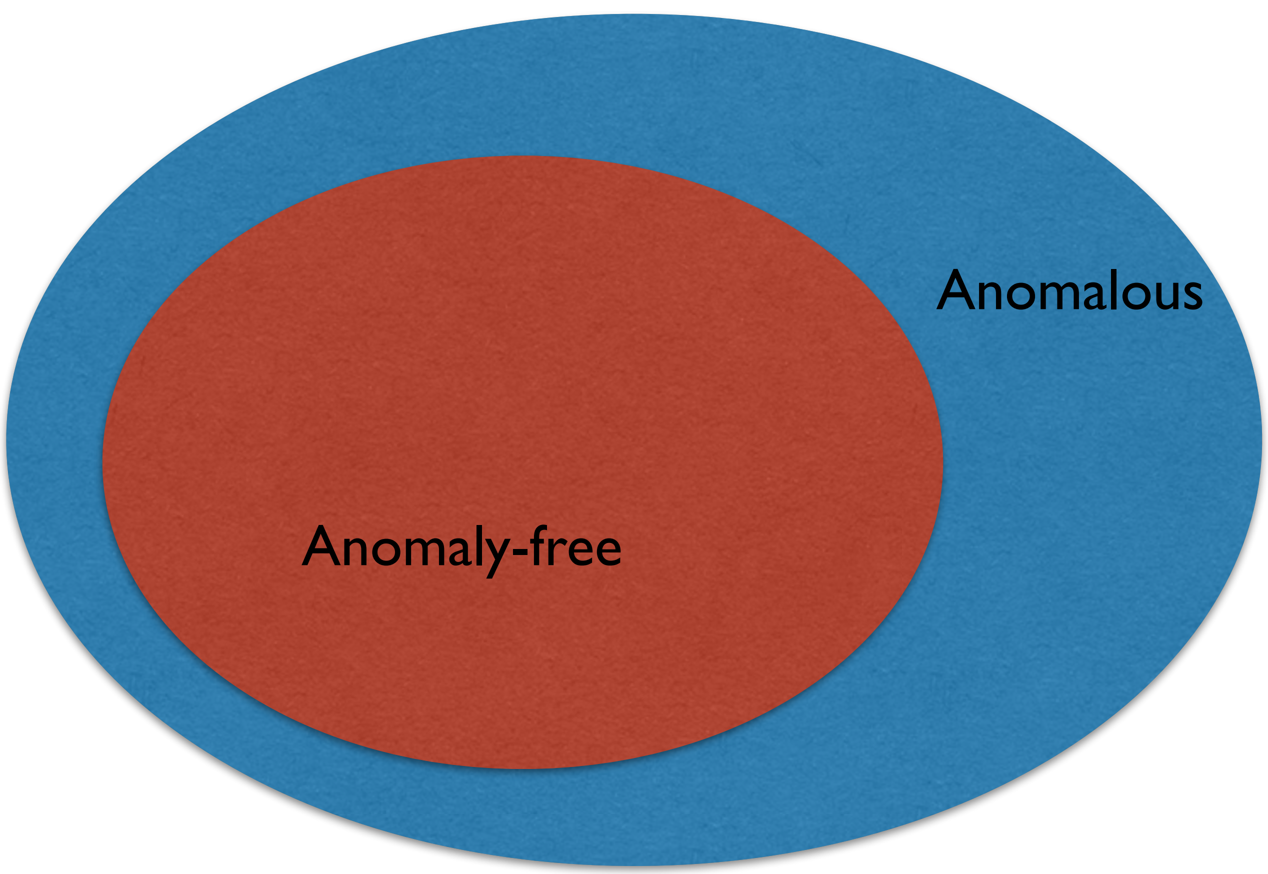
First guess: Anomalies

QFT of scalars and fermions → QFT of scalars and fermions + gauge fields

Anomaly constraints

example. QFT of one fermion with SU(2) global symmetry

There is a Witten anomaly when coupling the theory to a gauge field!



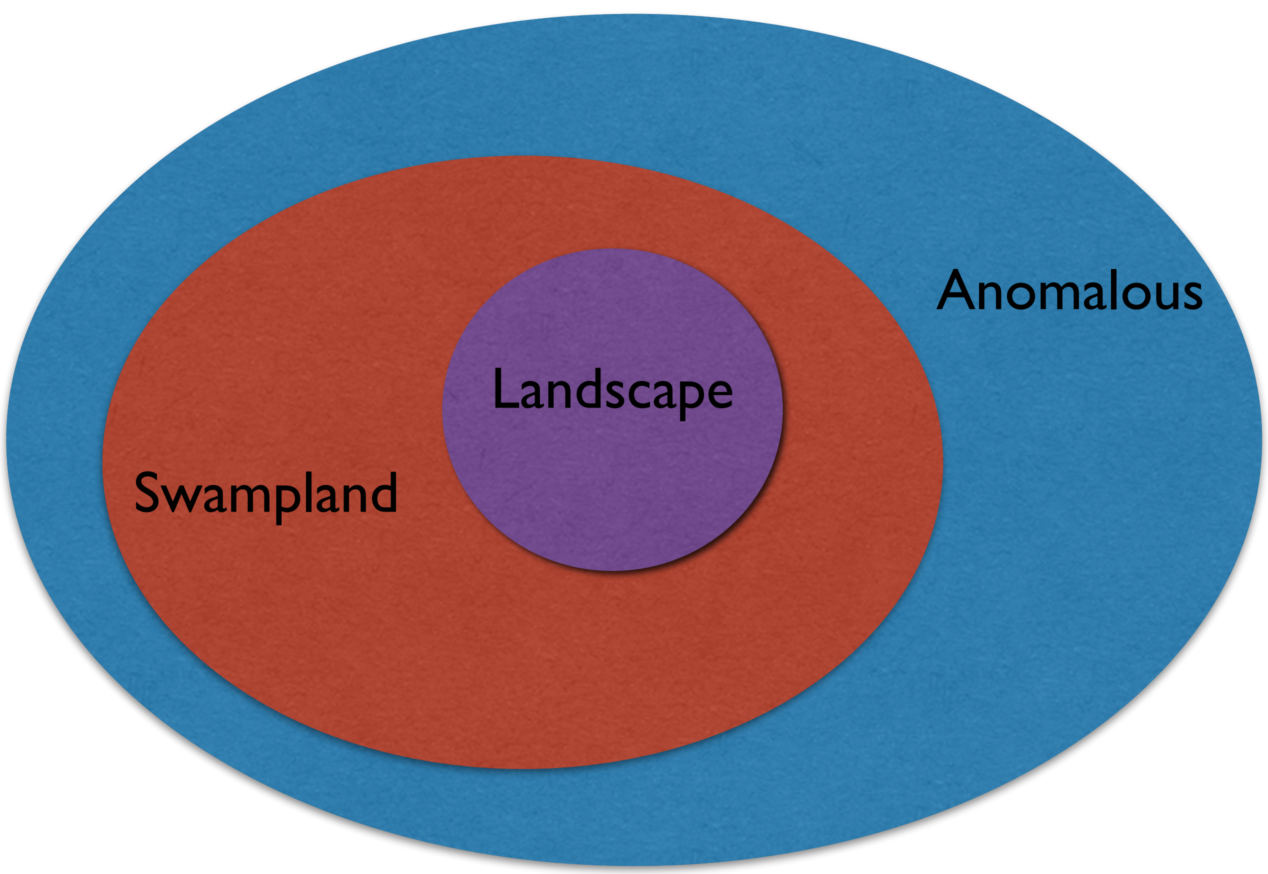
First guess: Anomalies

QFT of scalars
and fermions

Anomaly
constraints

QFT of scalars
and fermions
+ gauge fields

QFT of scalars
and fermions
+ gauge fields
+ gravity



First guess: Anomalies

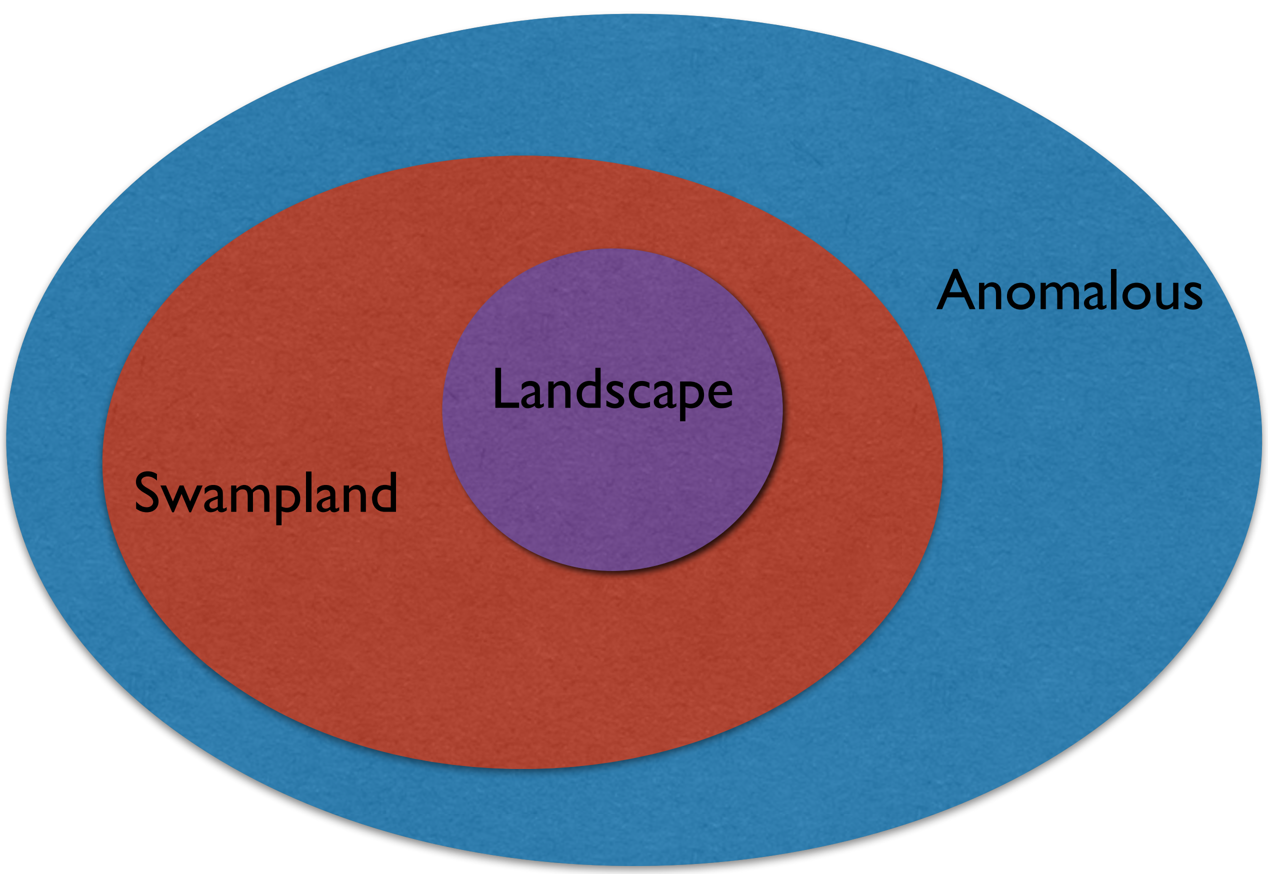
QFT of scalars and fermions

Anomaly constraints

QFT of scalars and fermions + gauge fields

Gravitational anomalies are not enough

QFT of scalars and fermions + gauge fields + gravity



Additional QG constraints!

There are additional (swampland/QG) constraints that any effective QFT must satisfy to be consistent with quantum gravity

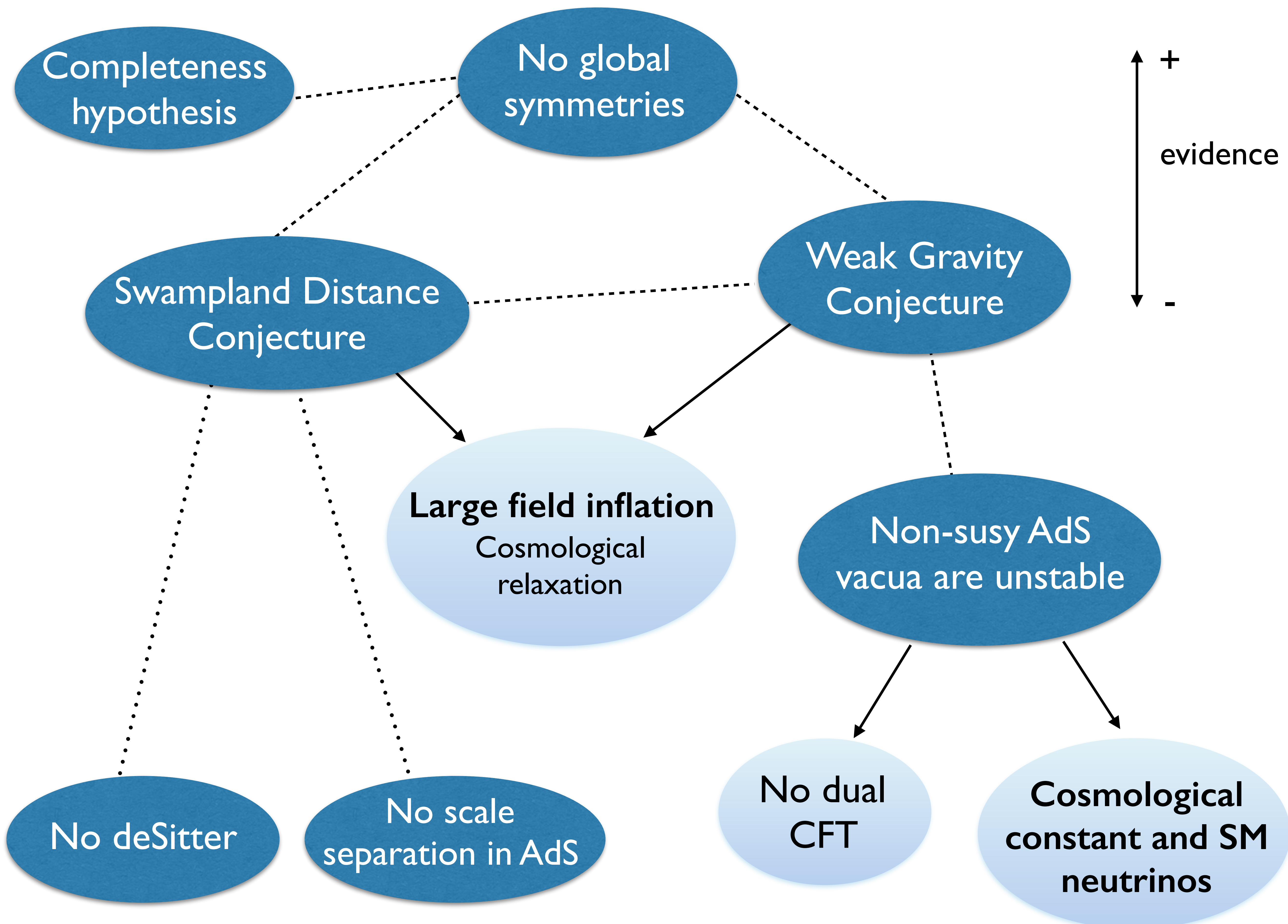
➡ UV imprint of quantum gravity at low energies

Outstanding phenomenological implications!

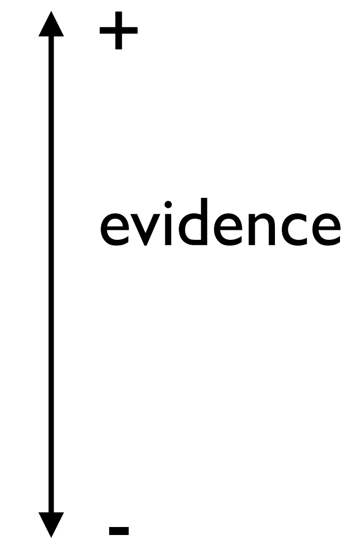
Proposals: **Quantum Gravity Conjectures**

(or Swampland Conjectures)

Motivated by String Theory as well as Black Hole physics



Completeness hypothesis
No global symmetries
+
evidence
-
Weak Gravity Conjecture
Swampland Distance Conjecture
Large field inflation
Cosmological relaxation
Non-susy AdS vacua are unstable
No deSitter
No scale separation in AdS
No dual CFT
Cosmological constant and SM neutrinos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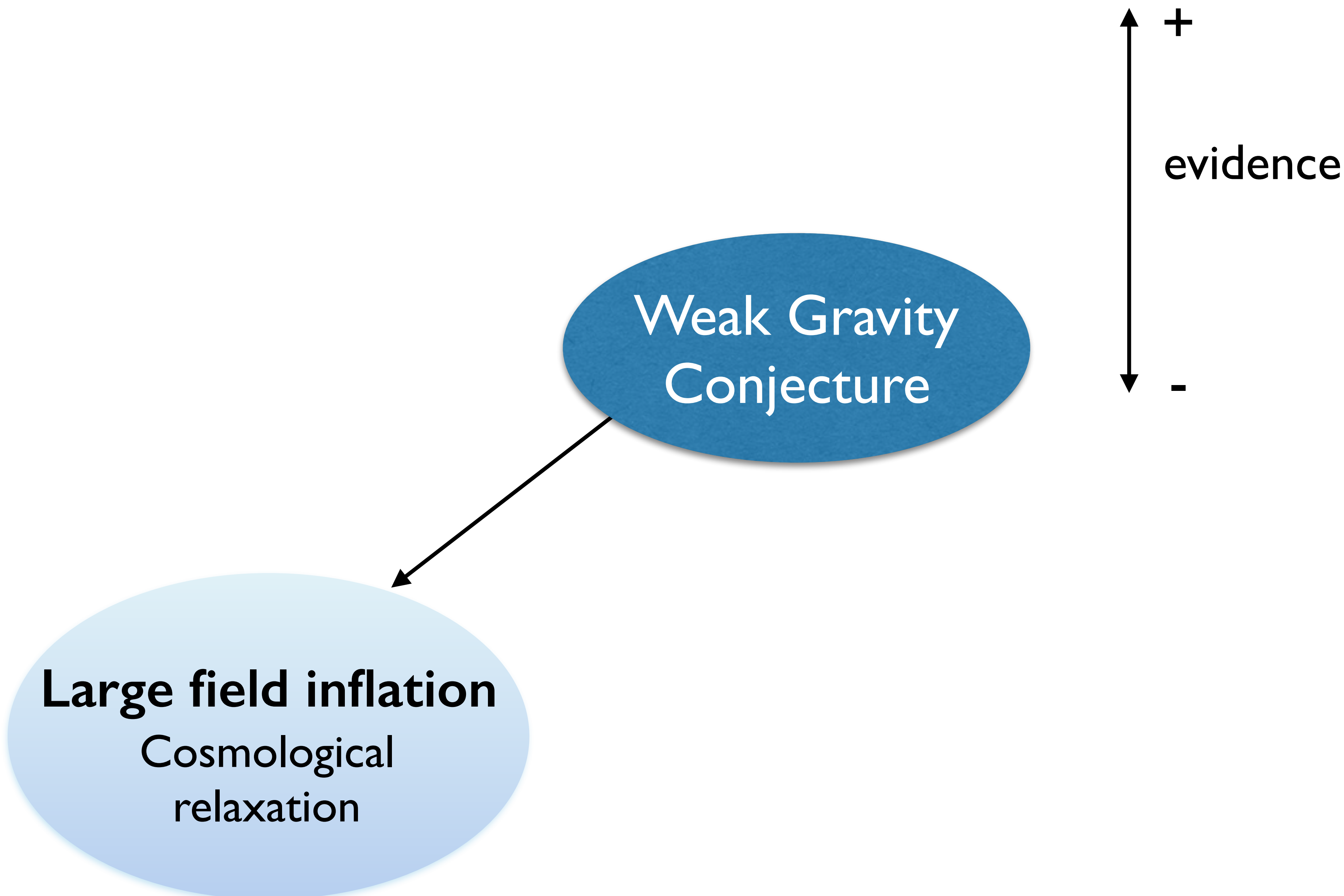
+
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Weak Gravity Conjecture
Large field inflation
Cosmological relaxation

Weak Gravity Conjecture

There exist at least a particle in which gravity acts weaker than the gauge force

$$\boxed{\frac{Q}{m} \geq 1}$$

Q : charge
m : mass

[Arkani-Hamed,Motl,Nicolis,Vafa'06]

Weak Gravity Conjecture

[Arkani-Hamed et al.'06]

Electric version:

Given an abelian gauge field, there must exist an electrically charged particle with

$$\frac{Q}{m} \geq \left.\frac{Q}{m}\right|_{\mathrm{extremal}} = 1$$

in order to allow extremal black holes to decay.

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Magnetic version:

The effective theory breaks down at a cut-off scale

$$\Lambda \leq g_{YM} M_p$$

which decreases as the gauge coupling goes to zero.

Weak Gravity Conjecture

[Arkani-Hamed et al.'06]

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Evidence:

- Plethora of examples in string theory (not known counter-example) [Lee et al'18-19] [Grimm et al'18-19] [Bonnefoy et al'18]
- Derivation from modular invariance of the 2d CFT [Heidenreich et al'16] [Montero et al'16]
- Relation to entropy bounds, unitarity and causality [Cottrell et al'16] [Andriolo et al'18]
- Derivation from higher derivative corrections to BH's [Fisher et al'17] [Hamada et al'18] [Cheung et al'18] [Charles'19] [Jones et al'19] [Cano et al'19]
- Relation to cosmic censorship [Crisford et al'17]
- Relation to thermodynamic arguments [Hod'17,] [Urbano'18]
- Relation to entanglement entropy [Montero' 19]

WGC for axions

[Rudelius, Heidenreich, Reece, Brown, Soler, Cottrell, Shiu, Bachlechner, Long, McAllister, Montero, I.V., Uranga,…]

Given an axion, there must exist an electrically charged instanton with

$$S \leq \frac{M_p}{f}$$

S : action (mass)

f : decay constant (inverse gauge coupling)

Induce a scalar potential: $V = Ae^{-S}\cos\left(\frac{\phi}{f}\right) + \sum_n \cancel{Ae^{-nS}\cos\left(n\frac{\phi}{f}\right)}$

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Perturbative control $S > 1$ + WGC $\rightarrow$ $f < M_p$

[Arkani-Hamed et al.'06] [Rudelius'15]

If instanton inducing the potential for inflation satisfies the WGC $\rightarrow$ Transplanckian axions (for large field inflation) are ruled out

WGC for axions

Loophole: “spectator instantons” [Brown et al.’15] [Bachlechner et al’15]

Instantons satisfying the WGC are not the same than those generating the inflationary potential

Million dollar question! Who must satisfy the WGC?

the lightest?
more than one?
small BH’s?

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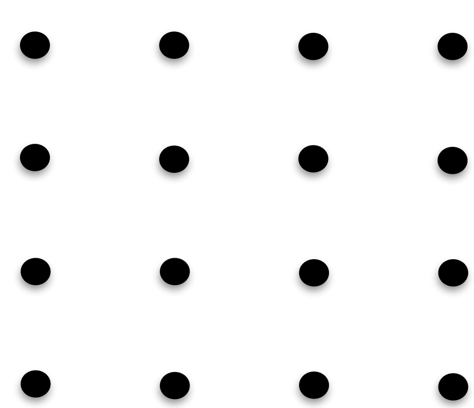
Different versions of the WGC (strong forms):

- (Sub)lattice WGC
- Tower WGC

consistency with dimensional reduction [Heidenreich et al.'15]
modular invariance of CFT [Montero et al.'15] [Heidenreich et al.'16]
analyticity and causality [Andriolo et al.'18]



$$S \leq \frac{|Q|}{f} M_p$$

Only instantons with small $|Q|$ will contribute significantly to the potential

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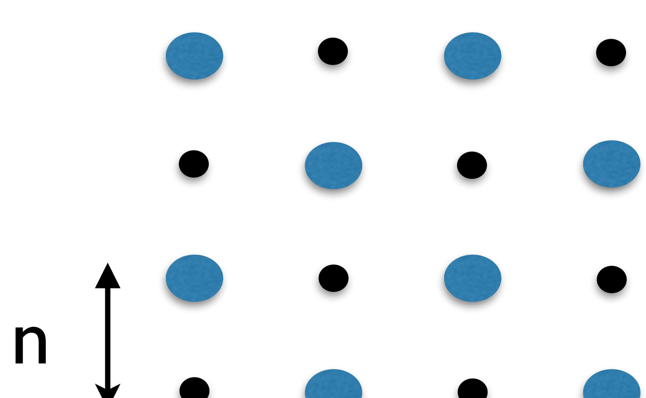
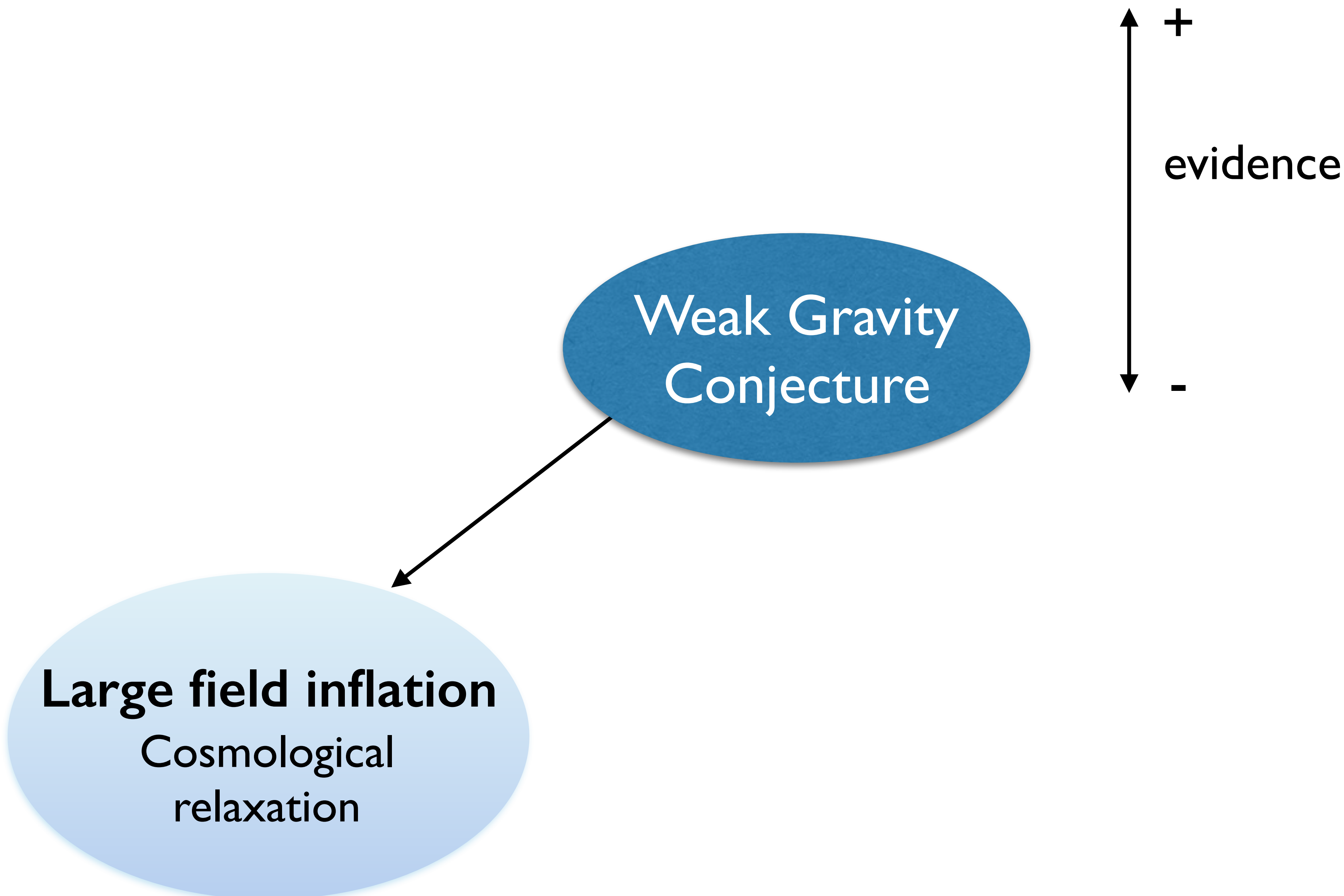


$$S \leq \frac{|Q|}{f} M_p$$

Constraints on inflation depend on index n of sublattice

[Heidenreich et al.'19]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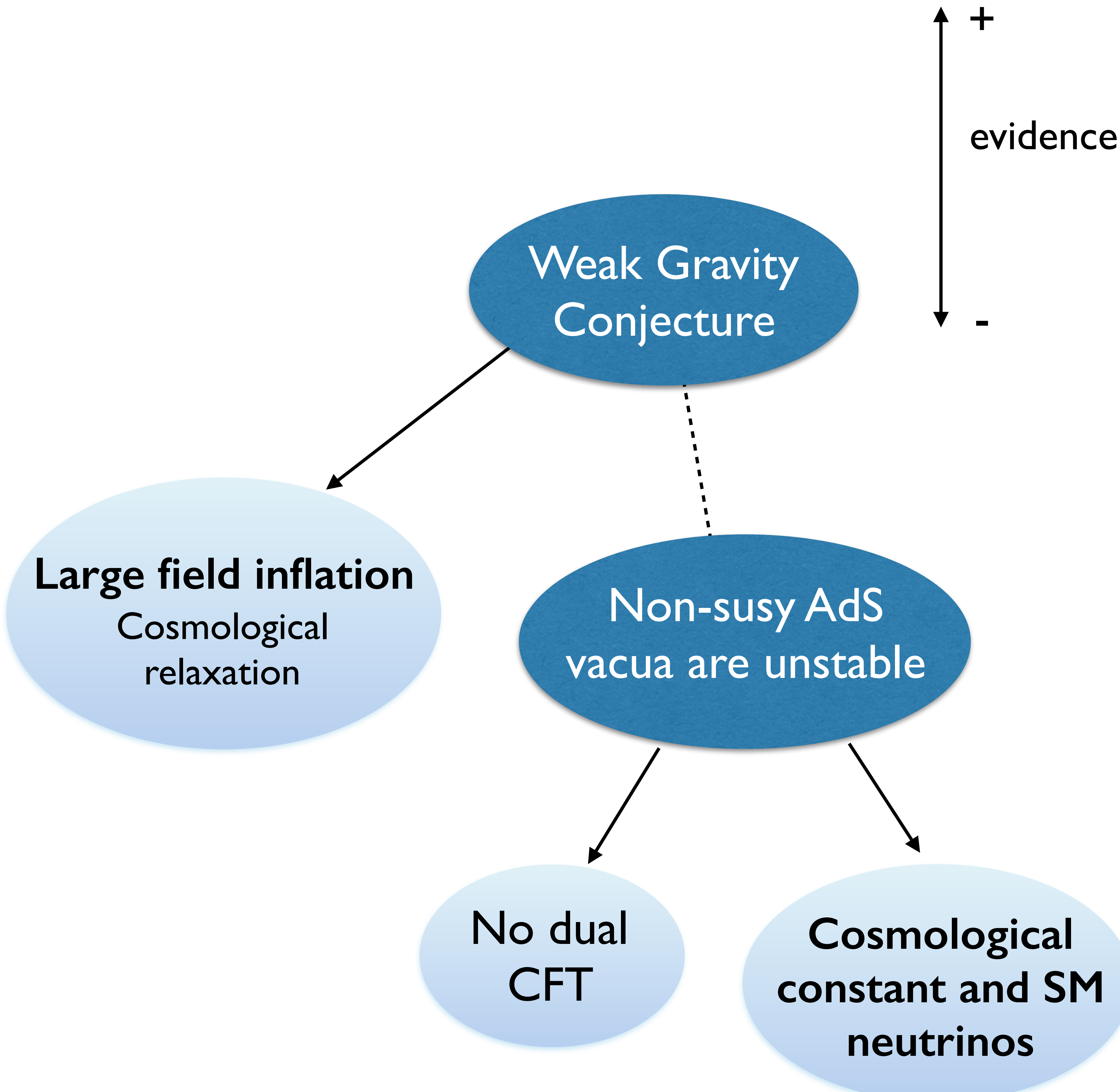

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$$\boxed{\frac{Q}{m} \geq 1}$$

Q : charge
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[Arkani-Hamed,Motl,Nicolis,Vafa'06]

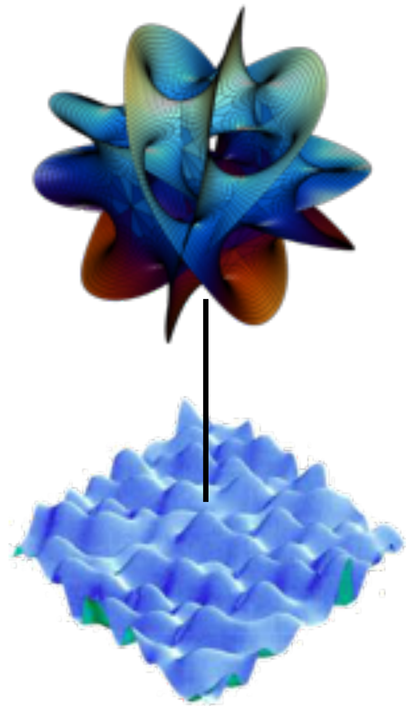
Sharpening of WGC:

$q = m$ only allowed if supersymmetric

[Ooguri-Vafa'17]

Weak Gravity Conjecture for fluxes

Extra dimensions



4d space-time

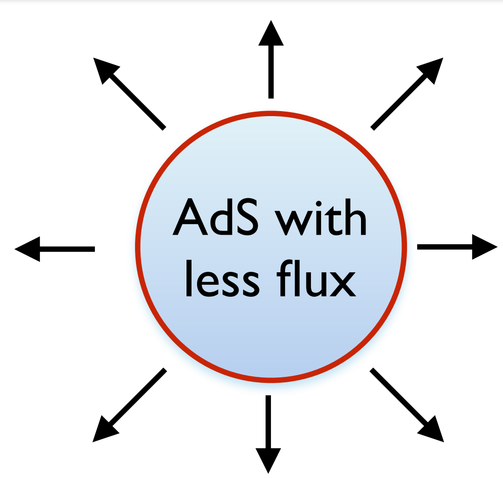
There can be gauge fields propagating in the extra dimensions

$$f_0 \sim \int_{\Sigma_p} F_p \quad \text{(fluxes in 4d)}$$

WGC applied to the fluxes (in a non-susy vacuum) implies: [Ooguri-Vafa'17]

$\exists$ Brane (domain wall) with $T < Q$ Bubble instability of the vacuum!

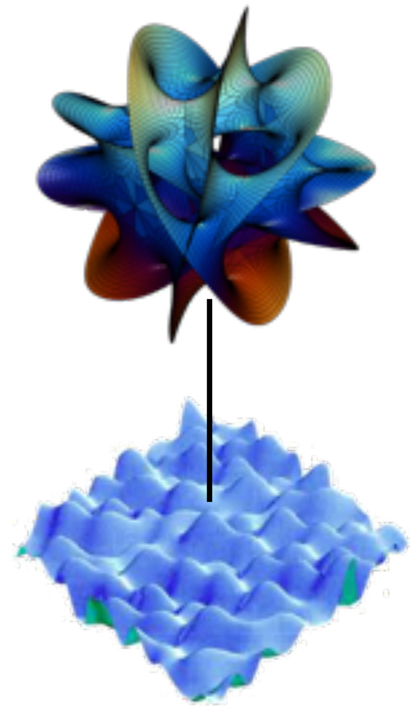
[Maldacena et al.'99]



AdS vacuum

Weak Gravity Conjecture for fluxes

Extra dimensions



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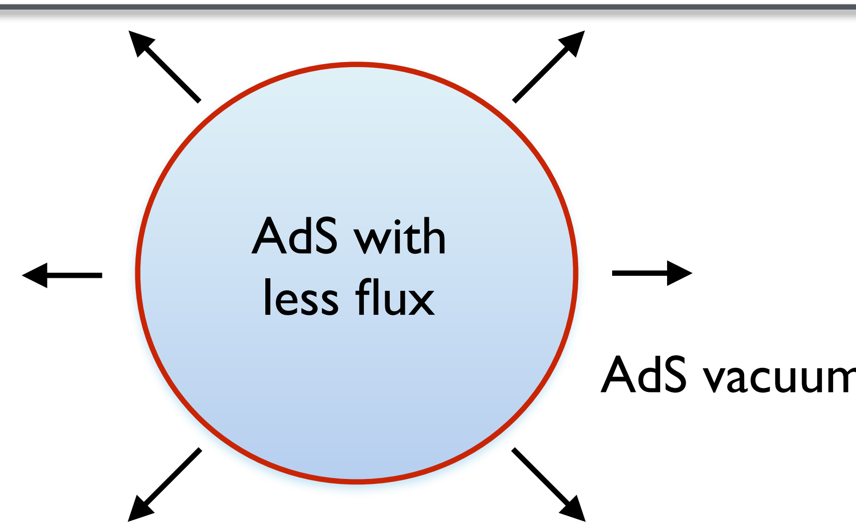

AdS Instability Conjecture

Non-susy vacua are at best metastable

[Ooguri-Vafa'16]
[Freivogel-Kleban'16]

Non-susy stable AdS vacua are in the Swampland
(inconsistent with Quantum Gravity)!

Implications:

- Non-susy CFT cannot have an Einstein gravity AdS dual
- Our universe must be metastable

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Implications:

- Non-susy CFT cannot have an Einstein gravity AdS dual
- Our universe must be metastable
- Constraints on BSM from studying lower dimensional AdS vacua arising from compactifications of the SM

Implications for Particle Physics

Notice: Standard Model compactified to lower dimensions can yield non-SUSY AdS vacua [Arkani-Hamed et al.'07] [Arnold-Fornal-Wise'10],

If stable, SM would be incompatible with quantum gravity!

Solution: Require absence of 3d AdS vacua → Constraints on light spectra of SM

[Ibanez,Martin-Lozano,IV'17]

(also [Hamada,Shiu'17])

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Lower bound on the cosmological constant in terms of the neutrino masses

[Ibanez,Martin-Lozano,IV'17]

➡ Majorana neutrinos are ruled out unless new light BSM fermions

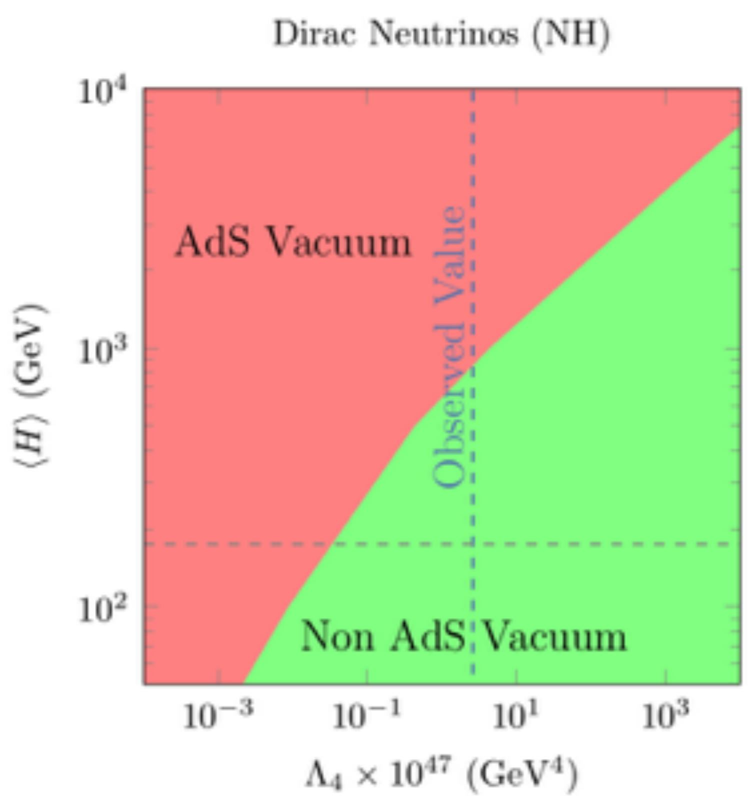
➡ SM by itself ruled out $\longrightarrow$ MSSM survives [Gonzalo,Herraez,Ibanez'18]

Translated to upper bound on the EW scale: $\langle H \rangle \lesssim 1.6 \dfrac{\Lambda^{1/4}}{Y_{\nu_1}}$

Naturalness?

Consistency with quantum gravity requires $\langle H \rangle \lesssim 1.6 \frac{\Lambda^{1/4}}{Y_{\nu_1}}$ [Ibanez,Martin-Lozano,IV'17]

(recall: sufficient but not necessary condition)



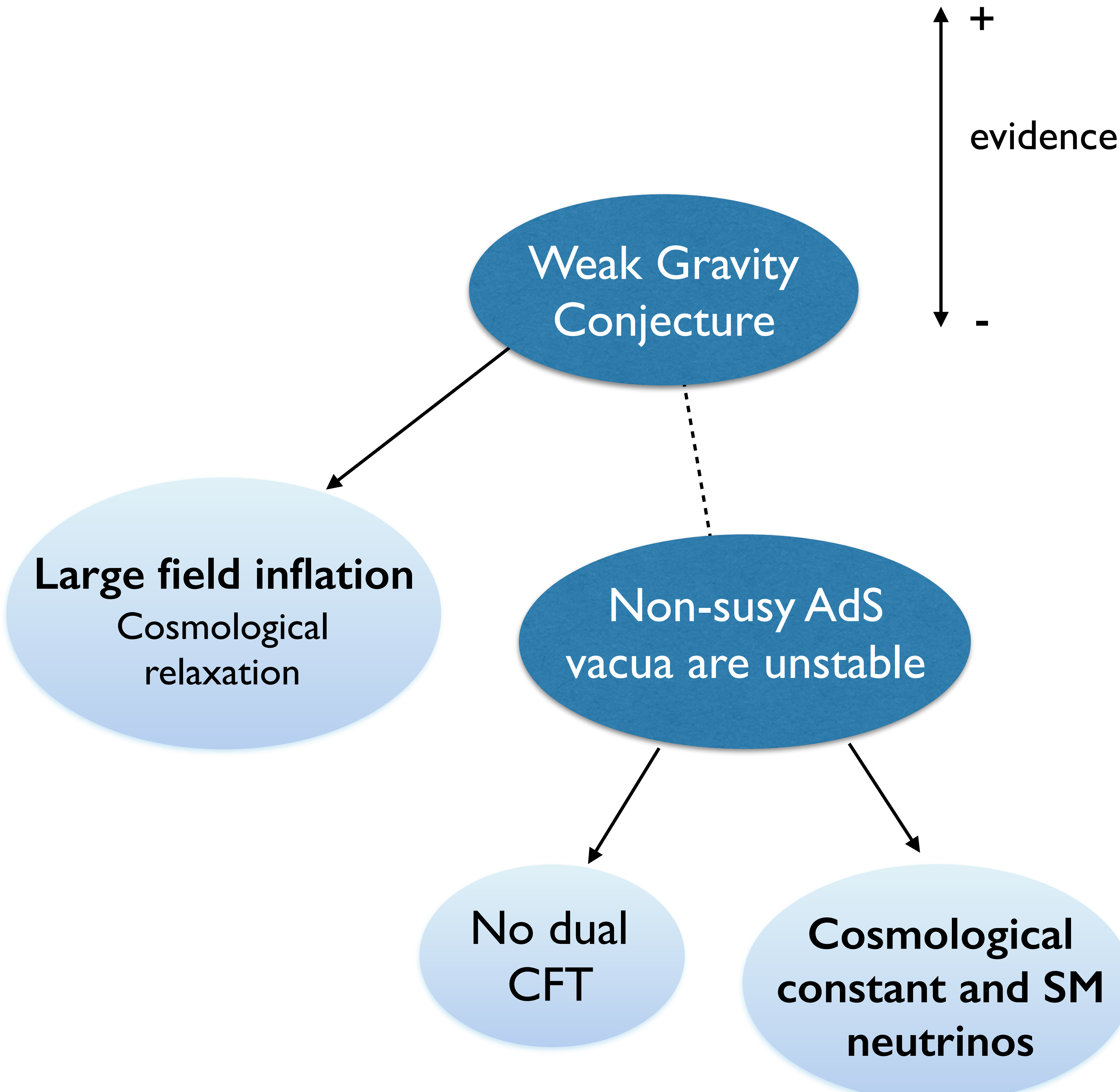
$Y = 10^{-14}$

Parameters leading to a higher EW scale do not yield theories consistent with quantum gravity

→ No EW hierarchy problem

New approach to fine-tuning/hierarchy problems?
UV/IR mixing from quantum gravity?

Naturalness might not be a good principle, not everything goes!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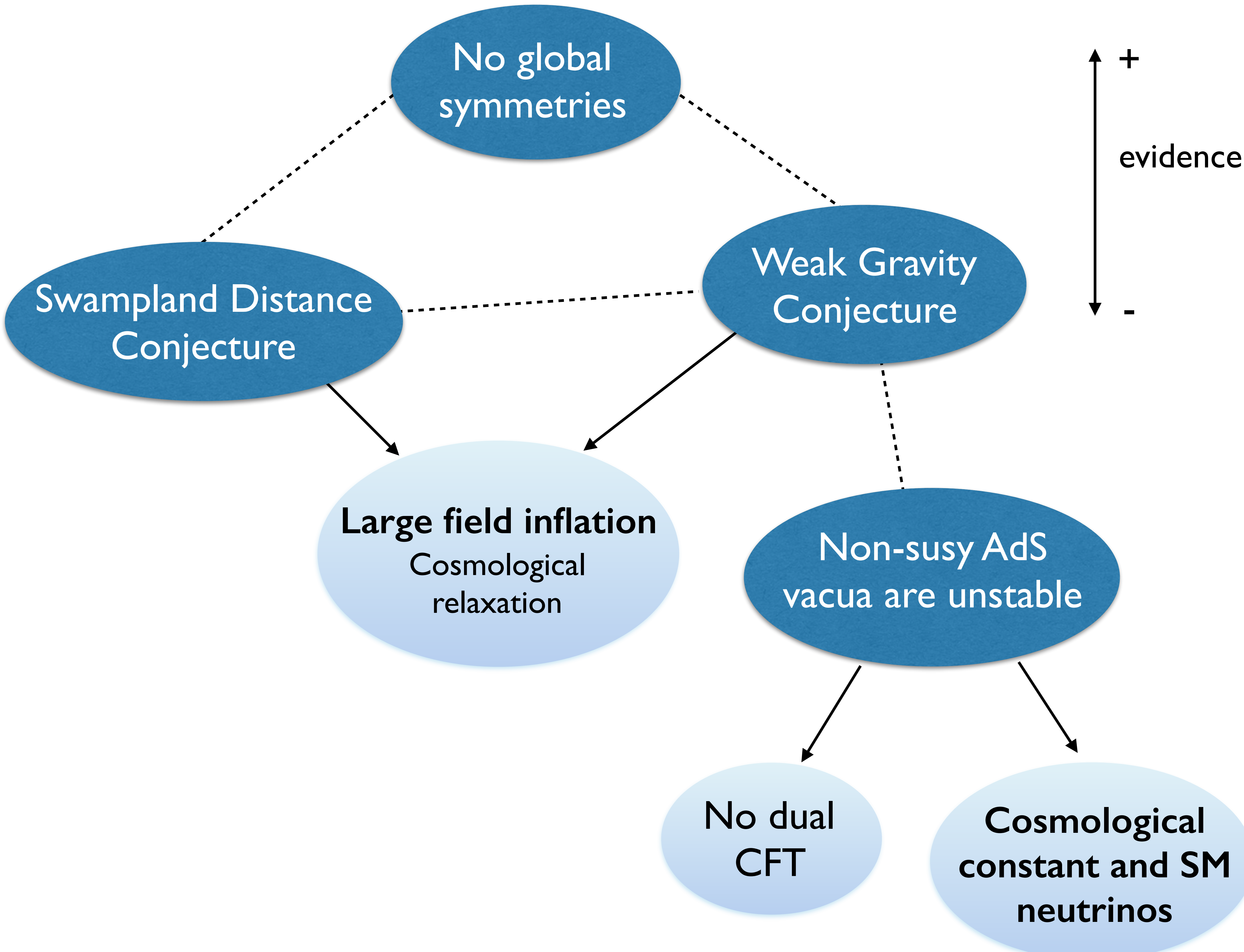
No global symmetries
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Absence of global symmetries

Any global symmetry must be broken or gauged

Evidence: Black Hole arguments [Banks-Dixon'88] [Horowitz,Strominger,Seiberg…]

Proof in AdS/CFT [Harlow,Ooguri '18]

It does not constrain the IR effective theory $\longrightarrow$ breaking can be very suppressed

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Exception: New swampland criterium $\Omega_k^{QG} = 0$ [McNamara,Vafa'19]

to avoid global symmetry from (d-k-1)-dim defects

It implies all theories are connected by finite energy domain walls, and predicts the existence of new defects in string theory!

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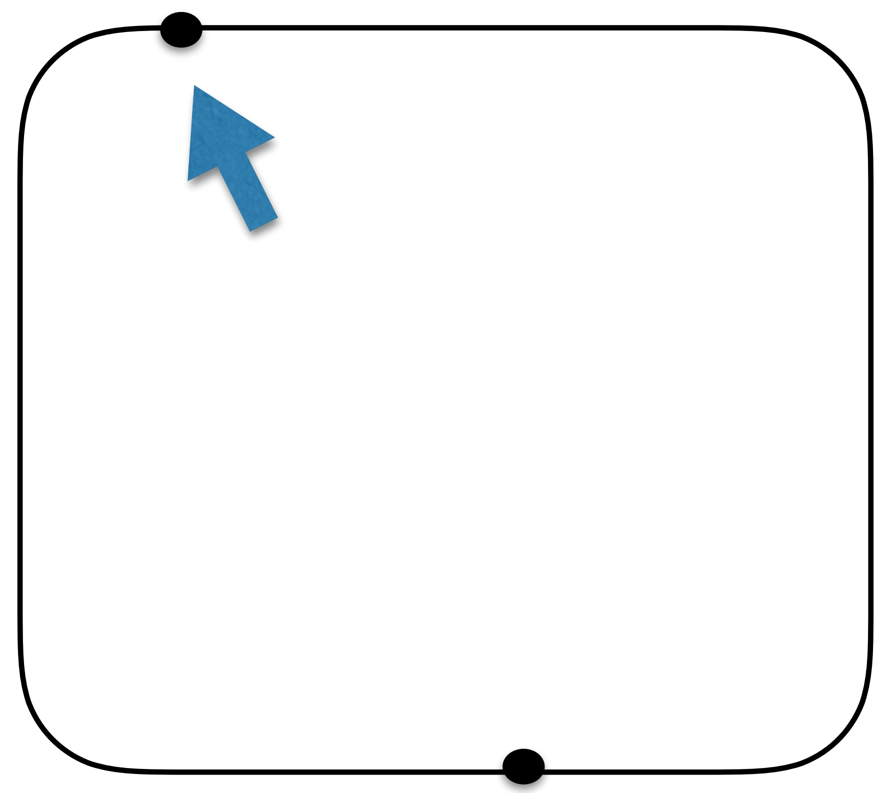
What about approximate symmetries? How badly broken? $\Rightarrow$ It can constrain the IR effective theory!

WGC and SDC quantify how 'approximate' a global symmetry can be

Approximate global symmetries

Parameter space:



Assume some global symmetry can be restored in a continuous way at some special points of the parameter space

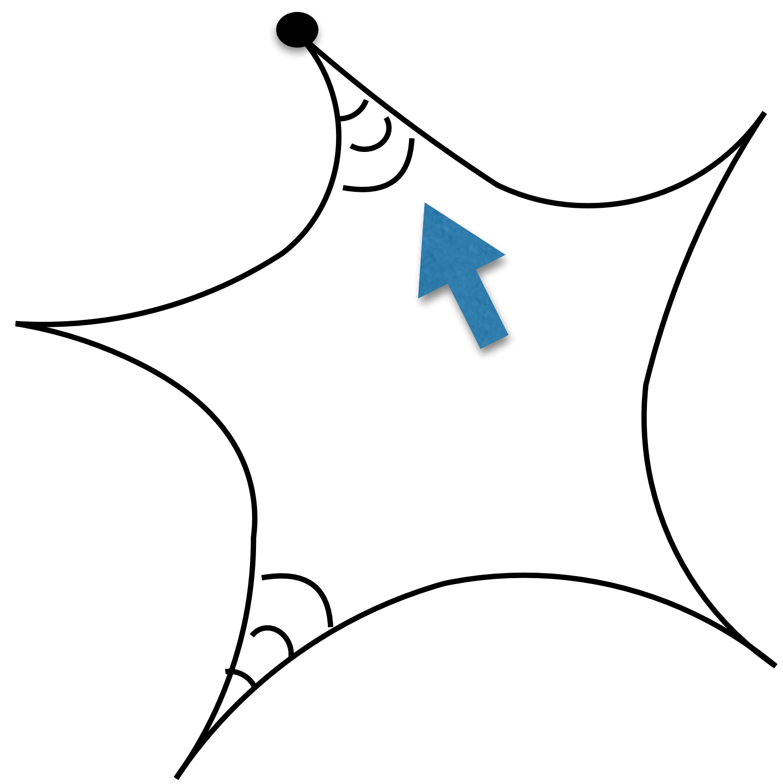
e.g. by sending gauge coupling $g_{YM} \to 0$
we restore a U(1) global symmetry

Approximate global symmetries

Parameter space:

=

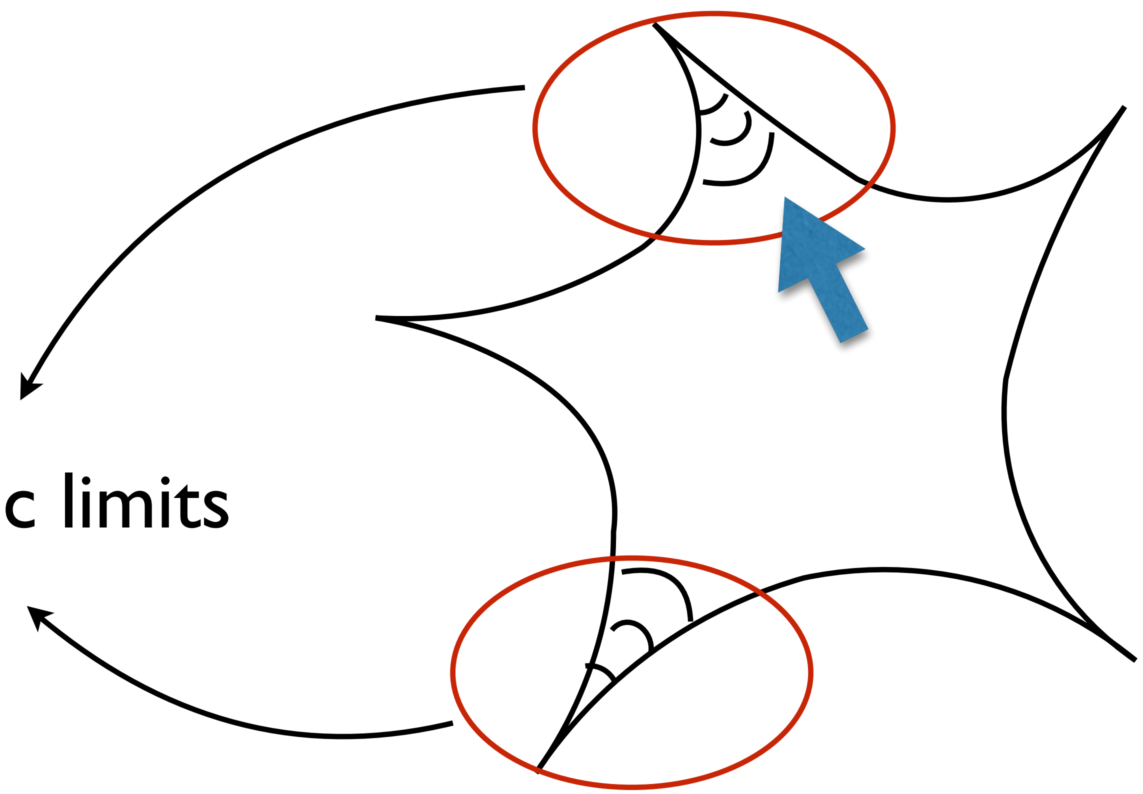
Field space in String Theory



Global symmetries are not allowed in quantum gravity

They can only be restored at infinite field distance (boundaries/singularities of the moduli space)

Approximate global symmetries

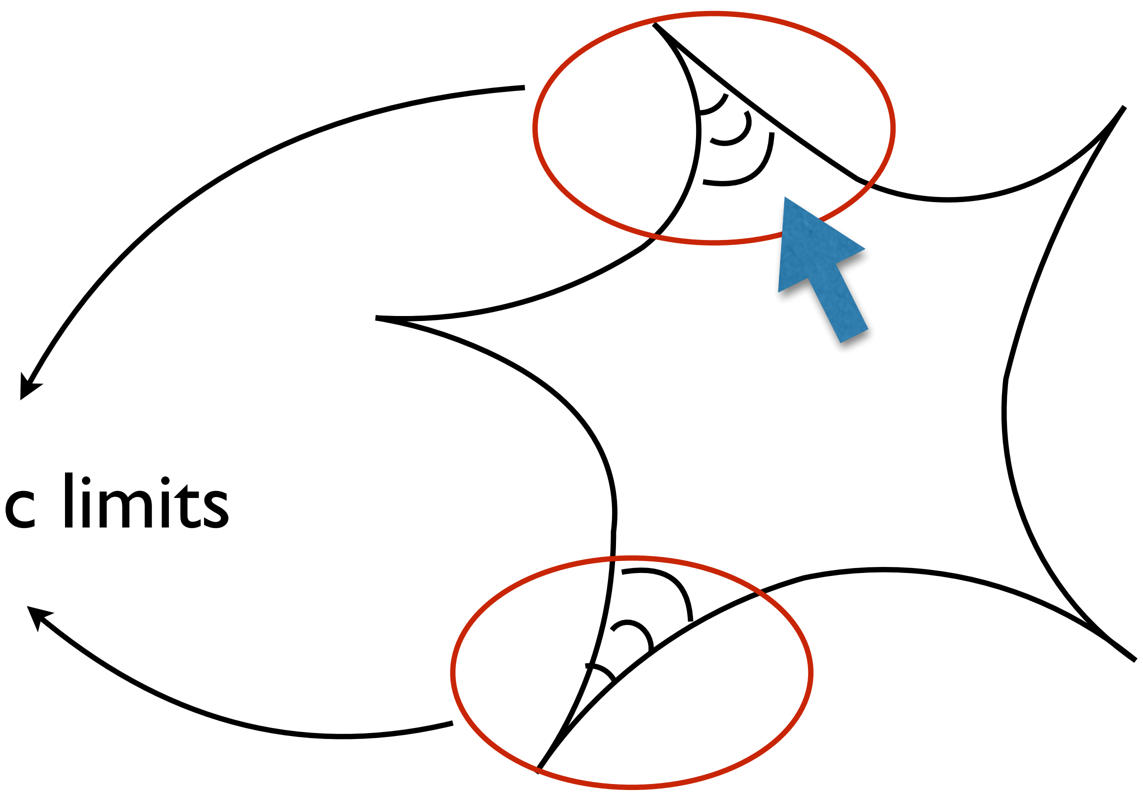


Asymptotic limits

Infinite distance loci:
special limits where a weakly
coupled description arises

(weakly coupled gauge theory,
approximate global symmetries…)

Approximate global symmetries



Asymptotic limits

Infinite distance loci:
special limits where a weakly coupled description arises

(weakly coupled gauge theory, approximate global symmetries…)

These limits seem under control from the point of view of QFT

but still, the EFT must break down when approaching the boundary by quantum gravity effects

WGC and global symmetries

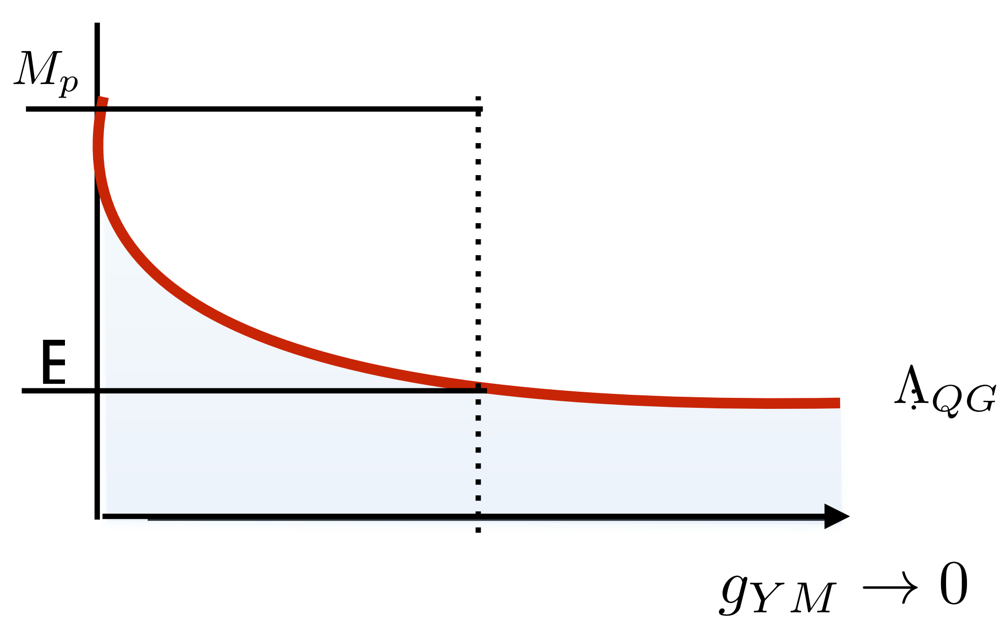
e.g. weak coupling limit: $g_{YM} \to 0$

Magnetic version of WGC:

Cut-off of effective theory $\Lambda \leq g_{YM} M_p \to 0$

(EFT breaks down continuously in the global symmetry limit)

WGC acts as a Quantum Gravity obstruction to restore a global symmetry



Distance Conjecture and global symmetries

e.g. global symmetry limit: $\Delta\phi \to \infty$

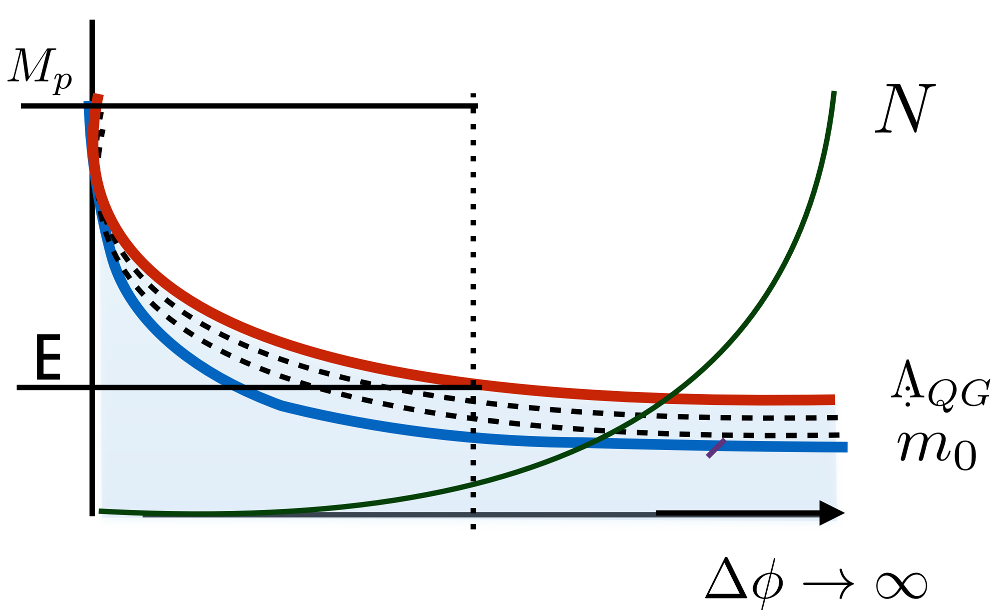
Distance conjecture:

Cut-off of effective theory $\Lambda \lesssim \Lambda_0 \, e^{-\lambda \Delta\phi} \to 0$

(EFT breaks down continuously in the global symmetry limit)

due to the presence of an infinite tower of states becoming light

SDC acts as a Quantum Gravity obstruction to restore a global symmetry



global symmetry limit = infinitely many massless species

Species scale: $\Lambda_{QG} = \dfrac{M_p}{\sqrt{N}}$

[Dvali'07]

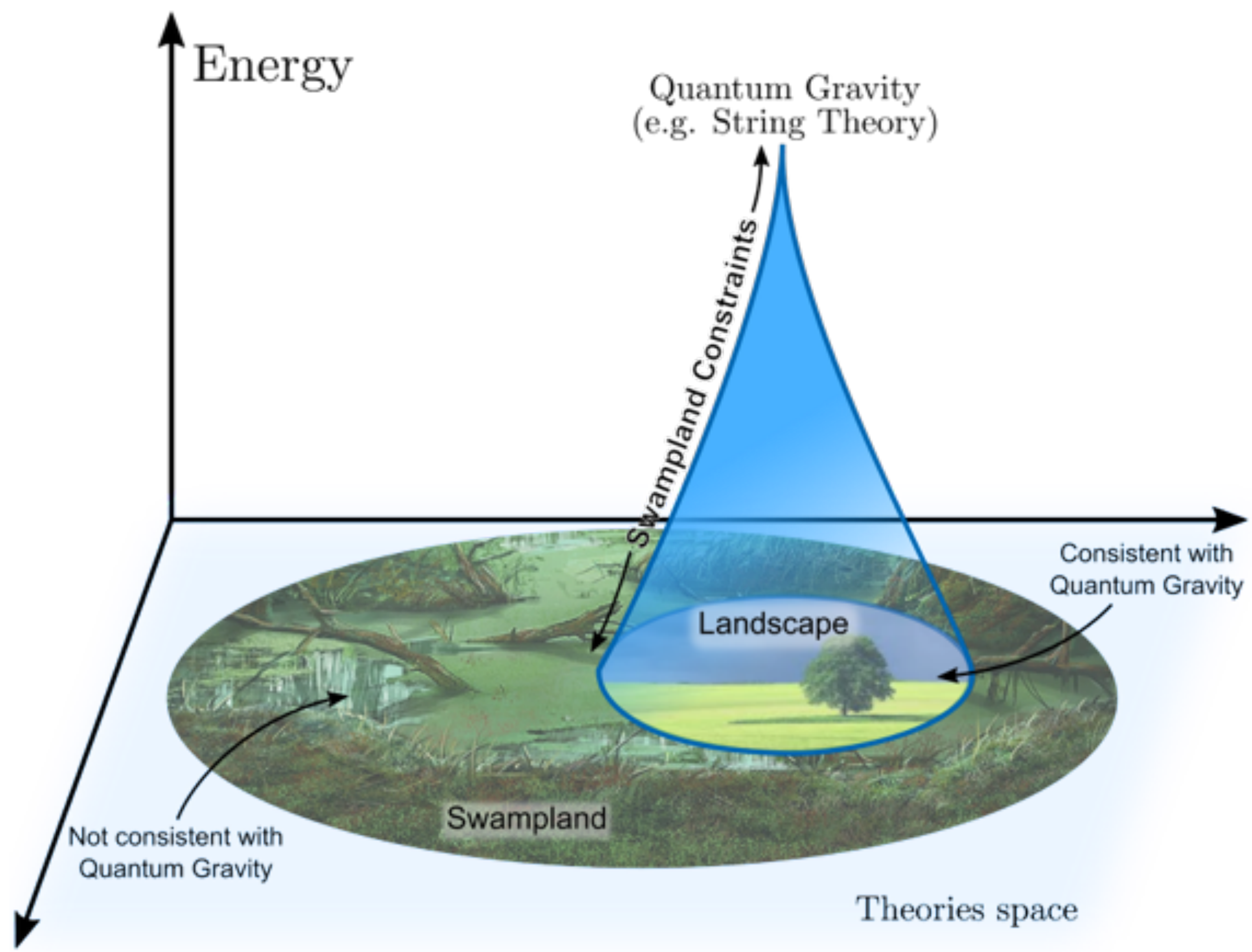
(scale at which QG effects become important)

Asymptotic limits

Swamppland Conjectures predict:

New physics → EFT breaks down below a cut-off that vanishes in the limit

New physics → Constraints the EFT: yield no-go's and universal patterns



Swampland Distance Conjecture [Ooguri-Vafa'06]

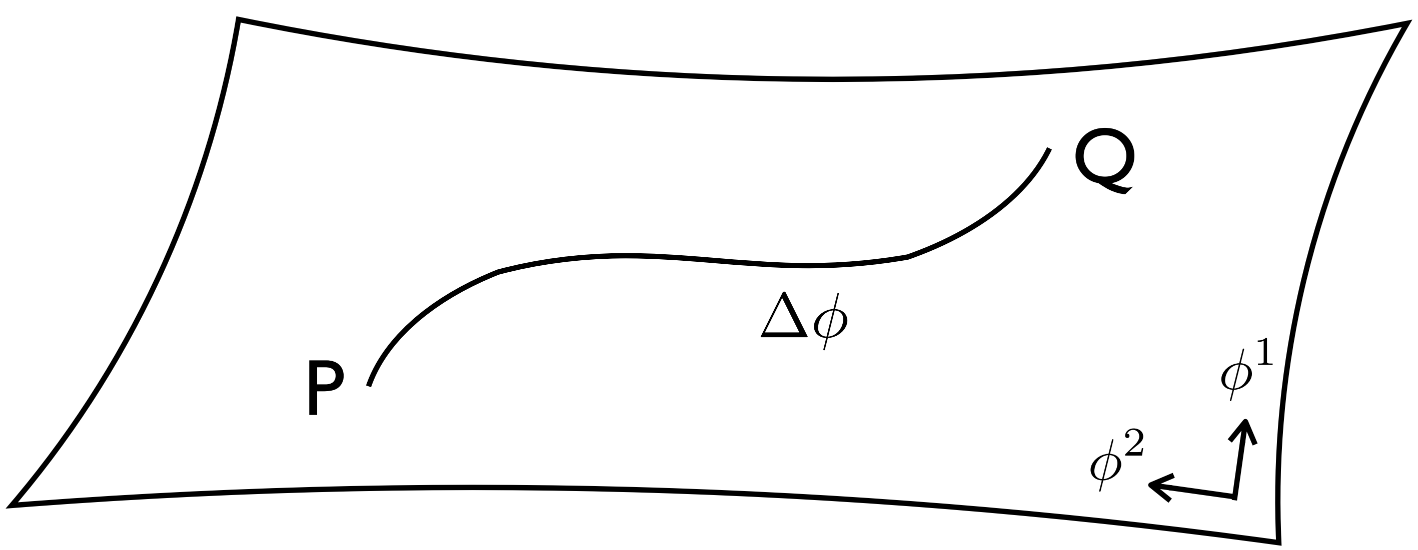
An effective theory is valid only for a finite scalar field variation $\Delta\phi$ because an infinite tower of states become exponentially light

$$m \sim m_0 e^{-\lambda\Delta\phi} \quad \text{when} \quad \Delta\phi \to \infty$$

This signals the breakdown of the effective theory:

$$\Lambda_{\text{cut-off}} \sim \Lambda_0 \exp(-\lambda\Delta\phi)$$

$\mathcal{L} = g_{ij}(\phi)\partial\phi^i\partial\phi^j$ ➔ scalar manifold (moduli space)



$\Delta\phi =$ geodesic distance between P and Q

$$m(P) \lesssim m(Q)e^{-\lambda\Delta\phi}$$

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$$\Lambda_{\text{cut-off}} \sim \Lambda_0 \exp(-\lambda\Delta\phi)$$

"Electric version" ? Proposal: 'Scalar WGC' [Palti'17] [Gonzalo, Ibanez'19]

Given a scalar force, $\mathcal{L} \supset m^2(\phi)\, h^2 \to (m\,\partial_\phi m)\,\phi\, h^2$
there must exist a particle with

$$m \leq \partial_\phi m \longrightarrow m \sim e^{-\phi}$$

Phenomenological implications

It gives an upper bound on the scalar field range that can be described by an effective field theory with finite cut-off

$$\Delta\phi \lesssim \frac{1}{\lambda}\log\left(\frac{M_p}{\Lambda}\right)$$

- **Large field inflation**
- **Cosmological relaxation of the EW scale**

If $H \leq \Lambda$

$$\Delta\phi \leq \frac{1}{\lambda}\log\frac{M_p}{H}$$

Phenomenological implications

It gives an upper bound on the scalar field range that can be described by an effective field theory with finite cut-off

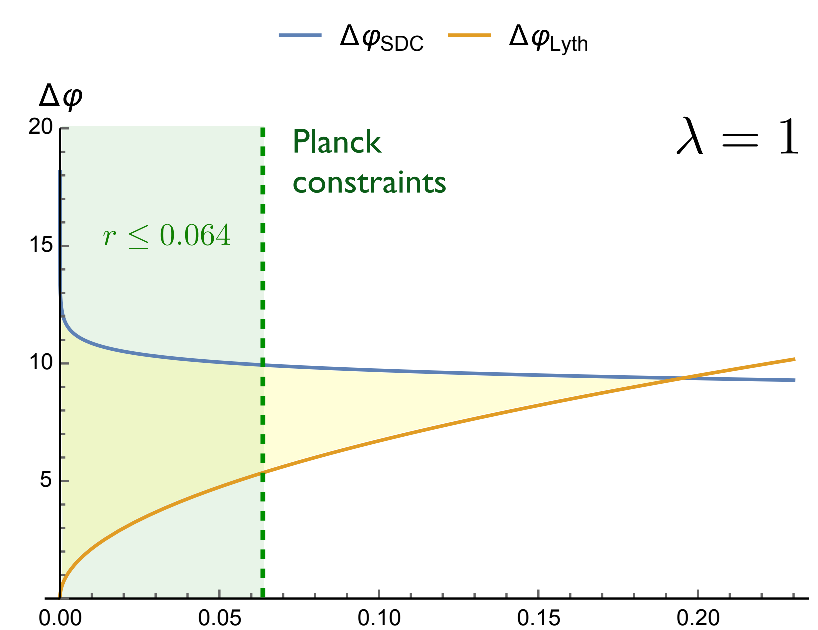
$$\Delta\phi \lesssim \frac{1}{\lambda}\log\left(\frac{M_p}{\Lambda}\right)$$

- **Large field inflation**
- **Cosmological relaxation of the EW scale**

If $H \leq \Lambda$

$$\Delta\phi \leq \frac{1}{\lambda}\log\frac{M_p}{H} \quad = \frac{1}{\lambda}\log\sqrt{\frac{2}{\pi^2 A_s r}}$$

Opposite scaling than Lyth bound!



[Scalisi,IV'18]

Phenomenological implications

It gives an upper bound on the scalar field range that can be described by an effective field theory with finite cut-off

$$\Delta\phi \lesssim \frac{1}{\lambda}\log\left(\frac{M_p}{\Lambda}\right)$$

Million dollar question! What is λ ?

Refined SDC: $\lambda \sim \mathcal{O}(1)$

Missing black hole argument: $\frac{\partial_\phi m}{m} \geq \lambda$

Evidence: based on particular examples in string theory compactifications

[Ooguri,Vafa'06] [Baume,Palti'16] [I.V.,'16] [Bielleman,Ibanez,Pedro,I.V.,Wieck'16] [Blumenhagen,I.V.,Wolf'17] [Hebecker,Henkenjohann,Witkowski'17] [Cicoli,Ciupke,Mayhrofer,Shukla'18][Blumenhagen et al.'18] [Grimm, Palti, IV'18] [Corvilain, Grimm, Palti'18] [Lee,Lerche,Weigand'18]

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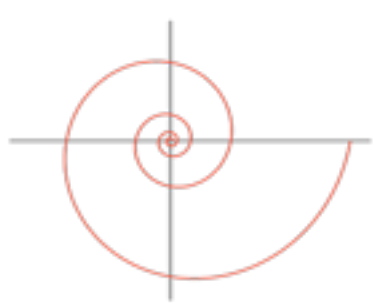
Missing black hole argument: $\frac{\partial_\phi m}{m} \geq \lambda$

Proposal: λ is related to the properties of a discrete infinite symmetry generating the tower of states [Grimm, Palti, IV'18]

$\longrightarrow$ lower bounded for geodesics

In general, it can depend on the trajectory



But….what type of trajectories and potentials are allowed by Quantum Gravity?

Evidence in String Theory

4d N=2 theories:

- Complex structure moduli space of Type IIB Calabi-Yau threefold

  Infinite towers of BPS states (wrapping D3 branes) [Grimm, Palti, IV'18] [Grimm,Palti,Li'18]

- Kahler moduli space of Type IIA Calabi-Yau threefold [Corvilain, Grimm, IV'18]

  Infinite towers of BPS states (wrapping D0-D2 branes) [Lee,Lerche,Weigand'18-19]

5d/6d N=1 theories:

- Kahler moduli space of M-theory/F-theory Calabi-Yau threefold

  Infinite towers of wrapping M2-branes/ tensionless strings

  [Lee,Lerche,Weigand'18-19] [Corvilain, Grimm, IV'18]

Beyond particle excitations:

- Towers of instantons (linked to WGC) [Marchesano,Wiesner'19] [Grimm,van de Heisteeg'19] [Baume,Marchesano,Wiesner'19]
- Membranes [Font,Herraez,Ibanez'19]

Evidence in String Theory

[Grimm, Palti, IV'18]

We can identify an infinite tower of BPS states becoming exponentially massless at every infinite field distance point of any Calabi-Yau threefold

Tools:

→ **Limiting Mixed Hodge Structures and Nilpotent Orbit Theorem:**
to compute growth of field metric and central charge (mass) of BPS states
(local universal expansion of the periods at infinite distance)

→ **Walls of marginal stability:**
to show stability of the orbit of BPS states generated by the monodromy transformation

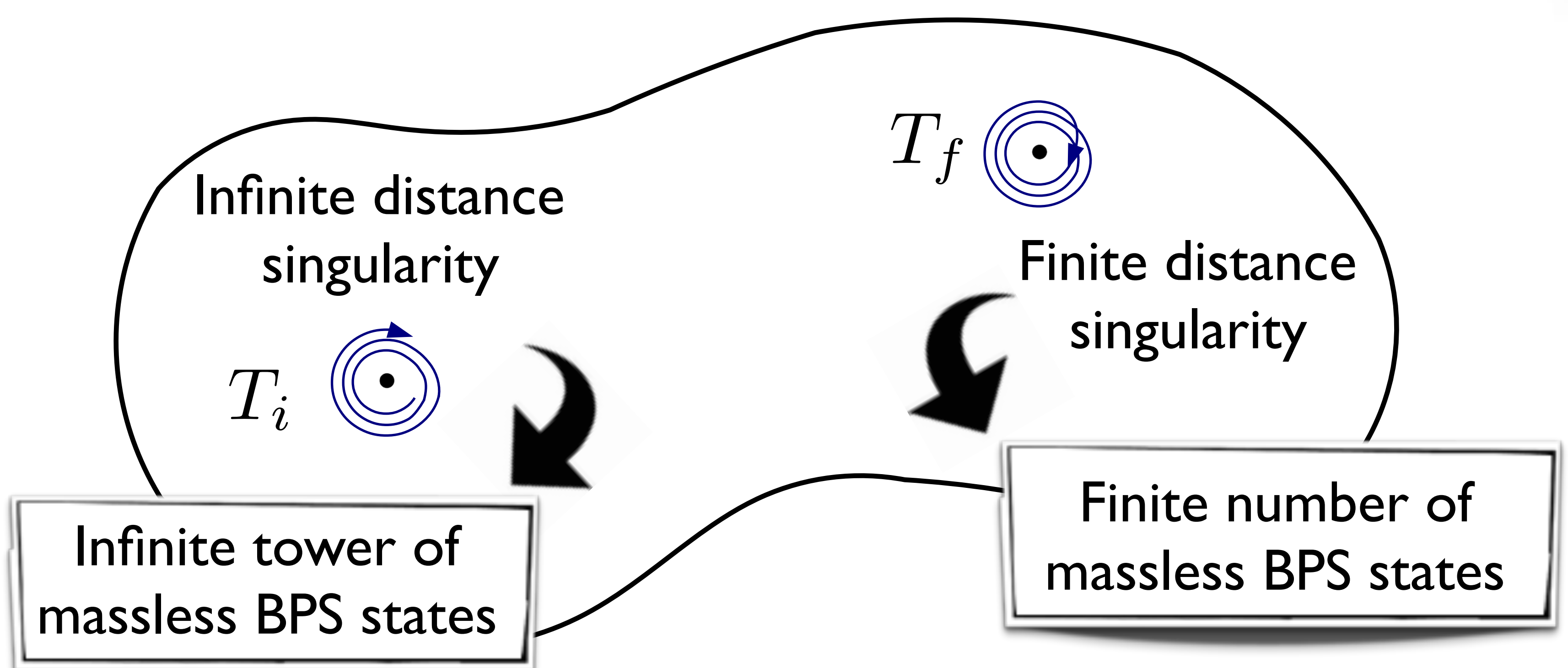
Techniques later used in: [Grimm,Palti,Li'18] [Corvilain, Grimm, IV'18] [Font,Herraez,Ibanez'19] [Grimm,van de Heisteeg'19]

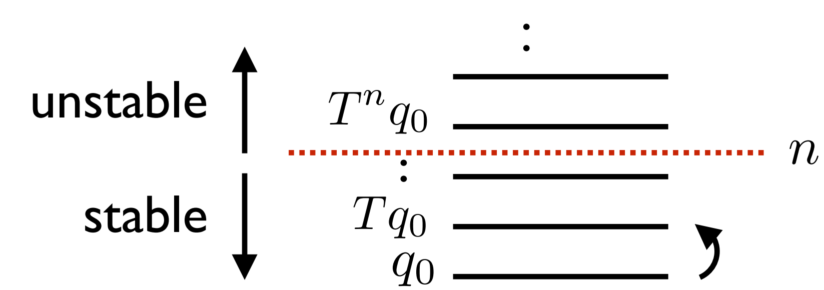
Evidence in String Theory

[Grimm, Palti, IV'18]

We can identify an infinite tower of BPS states becoming exponentially massless at every infinite field distance point of any Calabi-Yau threefold

Infinite distance → Monodromy of infinite order → Infinite tower of massless BPS states





$$n \sim e^{d_\gamma(P,Q)}$$

Types of asymptotic limits

- Geometrical classification in terms of the properties of the monodromy transformations

[Grimm, Palti, IV'18] [Grimm,Palti,Li'18] [Corvilain, Grimm, IV'18] [Li, Grimm, IV'18] [Lee,Lerche,Weigand' 19]

- **Proposal (Emergent string conjecture):** [Lee,Lerche,Weigand' 19]

Any infinite distance limit is either:

- Decompactfication limit
- Weakly coupled string theory limit (tensionless strings)

Gauge + Scalar fields

A lot of recent interest in configurations with both scalar + gauge fields

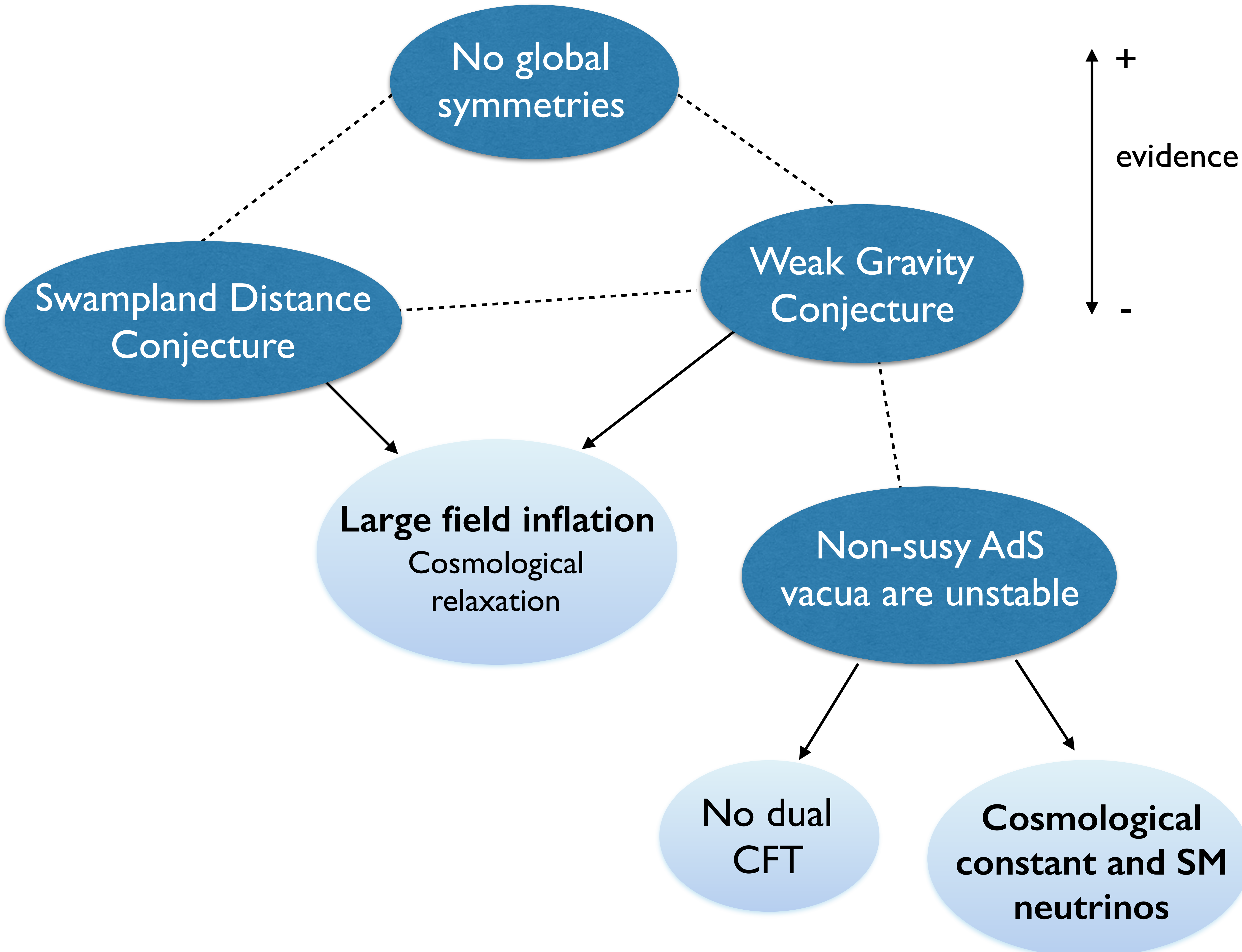
[Palti'16] [Lee,Lerche,Weigand'18] [Heidenrecih,Reece,Rudelius'19]

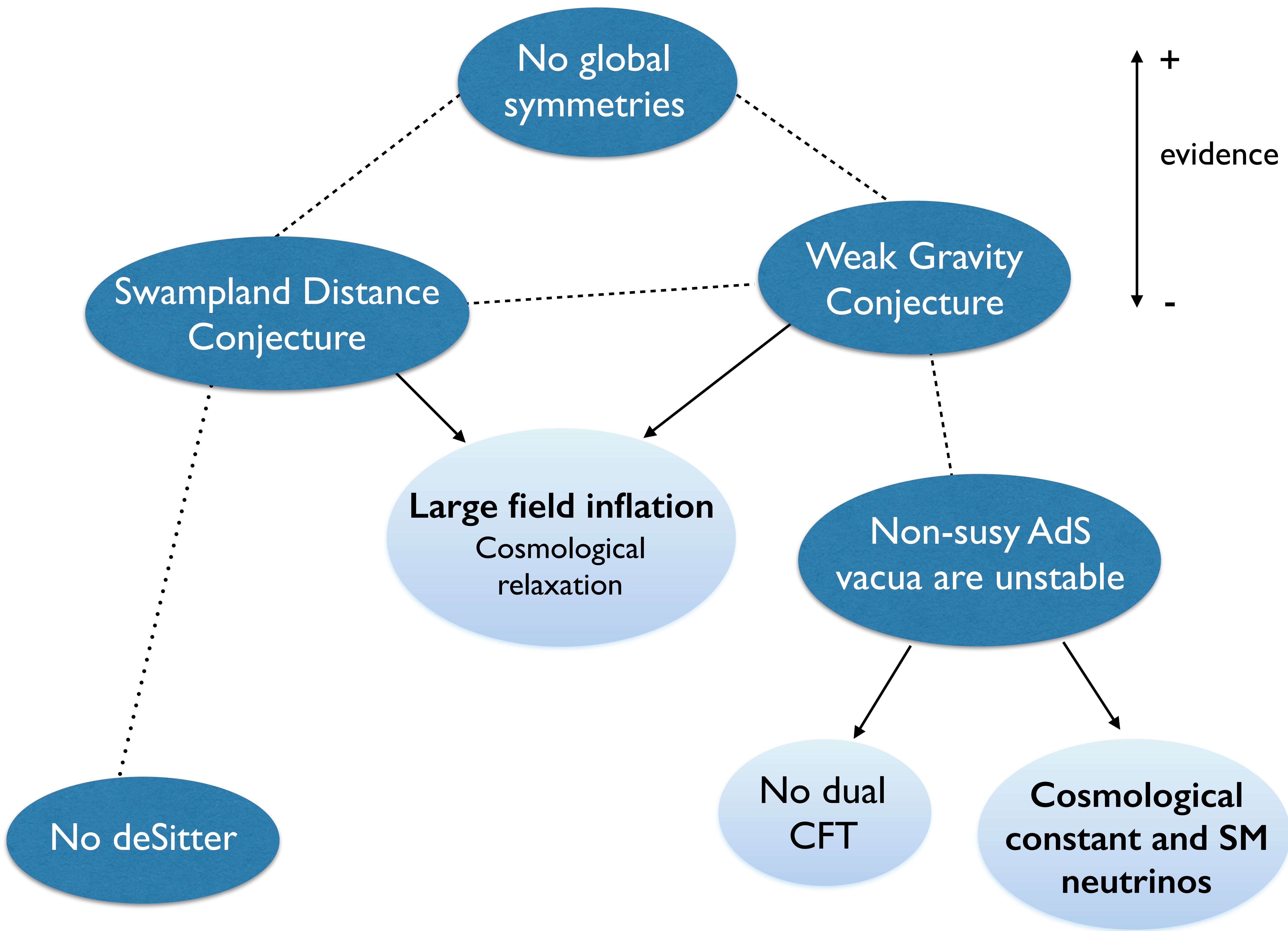
WGC with scalars: $\underbrace{q^2}_{\text{gauge force}} \geq \underbrace{m^2}_{\text{gravity}} + \underbrace{(\partial_\phi m)^2}_{\text{scalar force}}$ $\overset{\text{when??}}{=}$ $q^2 \geq \gamma(\phi) m^2$

(repulsive force conjecture)

(superextremality condition)

If infinite distance limit is a weak coupling limit: SDC = Tower WGC


No global symmetries
Swampland Distance Conjecture
Weak Gravity Conjecture
Large field inflation
Cosmological relaxation
Non-susy AdS vacua are unstable
No dual CFT
Cosmological constant and SM neutrinos
+
evidence
-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de Sitter conjecture

deSitter conjecture: $|\nabla V| \geq cV$ with $c \sim \mathcal{O}(1)$ [Obied,Ooguri,Spodyneik,Vafa'18]

Consistent with known no-go's for classical vacua in Type IIA

Evidence only based on particular examples…

[Hertzberg, Kachru, Taylor, Tegmark '08]
[Flauger,Paban,Robbin,Wrase '09]
[Wrase, Zagermann '10] …
[Wrase,Junghans,Andriot… '19]

Relation to the Swampland Distance Conjecture: [Ooguri,Palti,Shiu,Vafa '18]

The infinite tower of states is responsible of $|\nabla V| \geq cV$

(implying that the deSitter conjecture should be valid at any infinite distance point)

(not only large volume or string weak coupling)

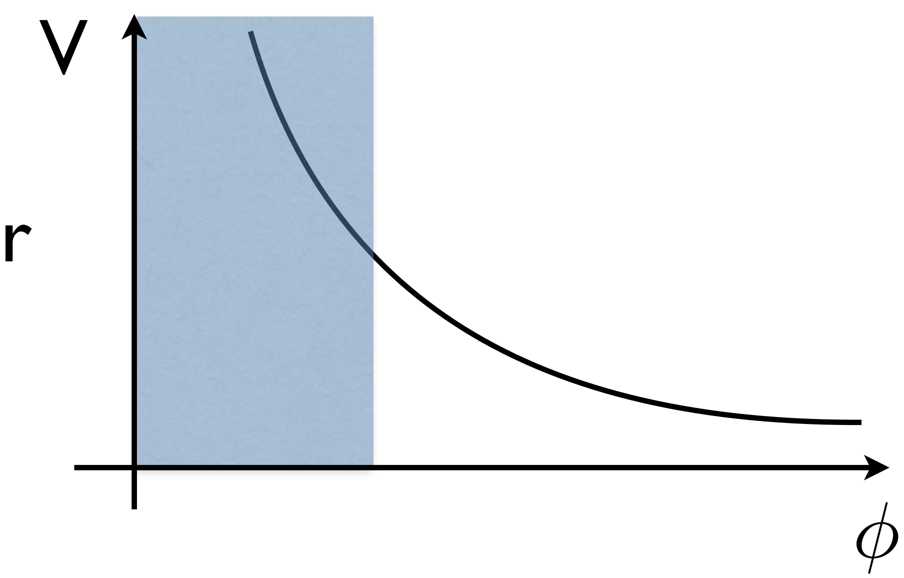
de Sitter conjecture

(asymptotic)

deSitter conjecture: $|\nabla V| \geq cV$ with $c \sim \mathcal{O}(1)$ [Obied,Ooguri,Spodyneik,Vafa'18]

at any asymptotic limit

→ Dine-Seiberg problem for every scalar (every direction in field space)



We need to go beyond string weak coupling limit to check the conjecture

Evidence in String Theory

M-theory on CY_4

$$V_{\rm M} = \frac{1}{\mathcal{V}_4^3}\Big(\int_{Y_4} G_4 \wedge * G_4 - \int_{Y_4} G_4 \wedge G_4\Big)$$

via F-theory duality: 4d flux compactifications

Using the same mathematical tools than for the SDC:

[Li, Grimm, IV '19]

We can determine the asymptotic structure of flux-induced potential at **any** asymptotic limit of the complex structure moduli space of CY_4

(including strong coupling limits)

$$\|G_4^{\boldsymbol{\ell}}\|^2_{\rm sl(2)} = \underbrace{\left(\frac{s^1}{s^2}\right)^{\ell_1 - 4} \cdots \left(\frac{s^{\hat n-1}}{s^{\hat n}}\right)^{\ell_{\hat n -1} - 4} (s^{\hat n})^{\ell_{\hat n} - 4}}_{s\ :\ \text{saxions}} \underbrace{\|\rho_{\boldsymbol{\ell}}(G_4, \phi)\|^2_\infty}_{\phi\ :\ \text{axions}}$$

ℓ_i : integers determined by he the singularity type

$$\rho(G_4,\phi) \equiv e^{\phi^i N_i} G_4$$

Evidence in String Theory

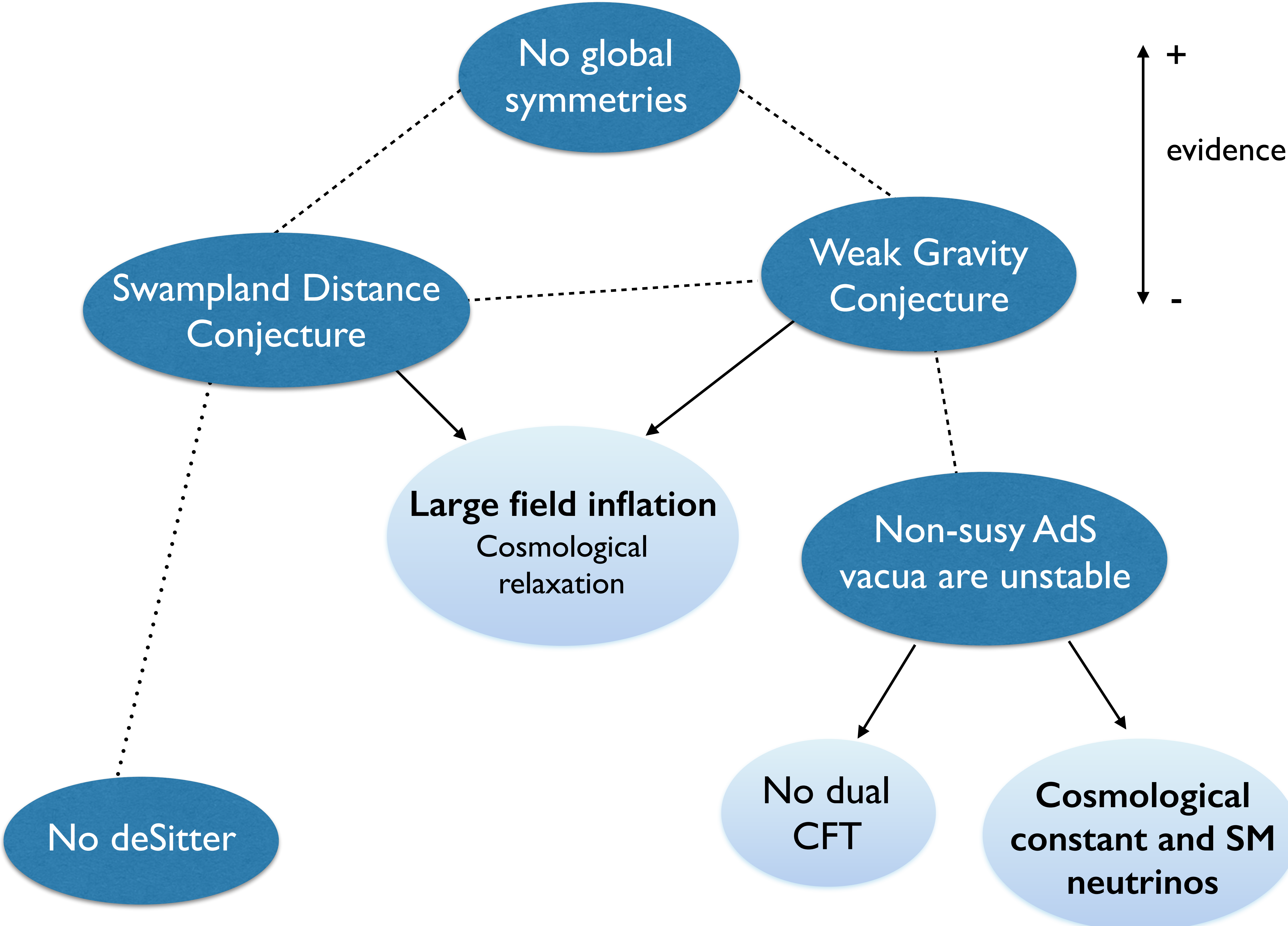
No-go theorem: [Li, Grimm, IV '19]

There is no dS vacua at parametric control near any two large field limit of a CY_4 in the strict asymptotic approx if $V \to 0$ at the large field limit

The potential satisfies the deSitter conjecture at any infinite distance limit in which an infinite tower of states can be identified

$\longrightarrow$ Linked to Distance conjecture

Future task: What about finite distance limits?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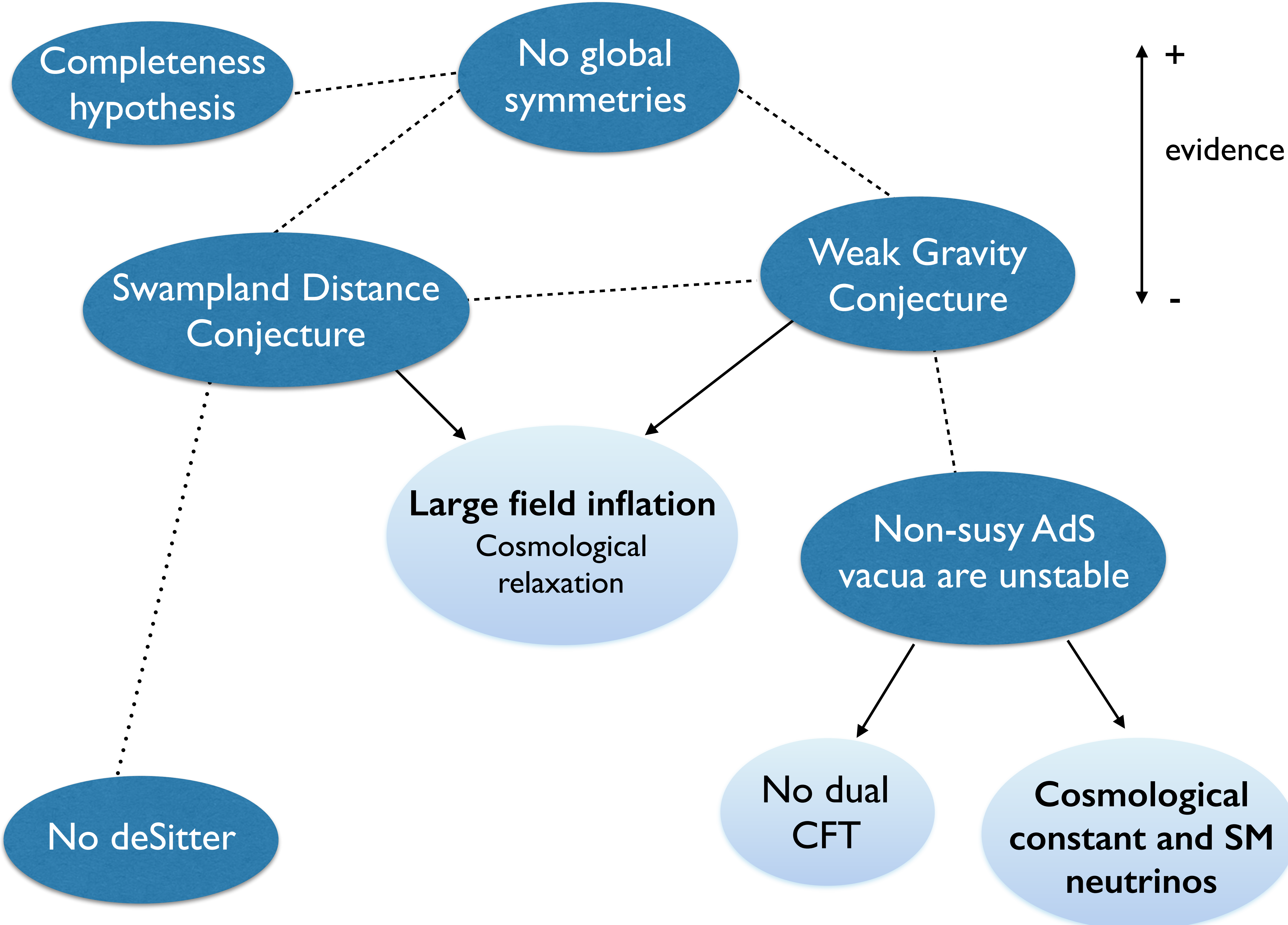
Completeness hypothesis
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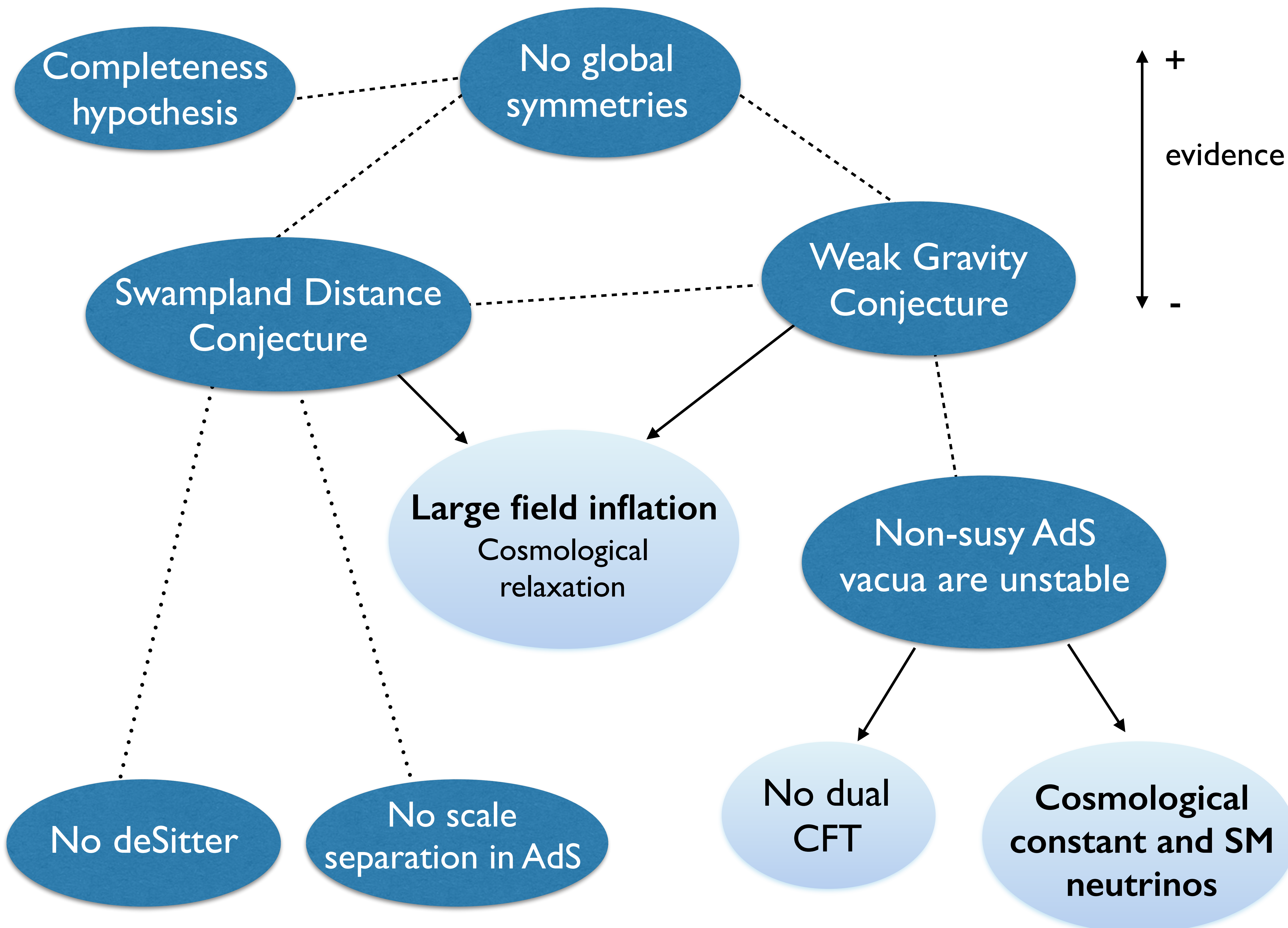
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No deSitter
No scale separation in AdS
No dual CFT
Cosmological constant and SM neutrinos

Why the conjectures should hold true in general?
Underlying principle?

[Harlow '15] [Grimm, Palti, IV '18]
[Heidenreich,Reece,Rudelius'17-18]
[Harlow, Ooguri, '18]

Emergence proposal

The IR kinetic terms of all fields emerge from quantum corrections of integrating out an infinite tower of states

(i.e. fields are not dynamical in UV, all kinetic terms vanish)

Infinite distance
Weak gauge coupling
Runaway potential

SDC/WGC →

← Emergence

Infinite tower of states
(specific structure) ★

★ Increasing number of states as we approach the global symmetry limit:

Drop-off of the cut-off = Species scale $\Lambda_{QG} = \frac{M_p}{\sqrt{N}}$

The swampland conjectures emerge from QFT renormalisation

Summary

- Network of conjectures (different faces of the same principle?)

- Phenomenological implications for inflation and particle physics!
  To be more precise is necessary to clarify the specific definition of the conjectures first.

- Significant new evidence in favour of the conjectures in the past years from different research areas.

- Interesting relations with Mathematics (Mixed Hodge Structures, Modular forms…)

Swampland workshops

The String Swampland and Quantum Gravity Constraints on Effective Theories

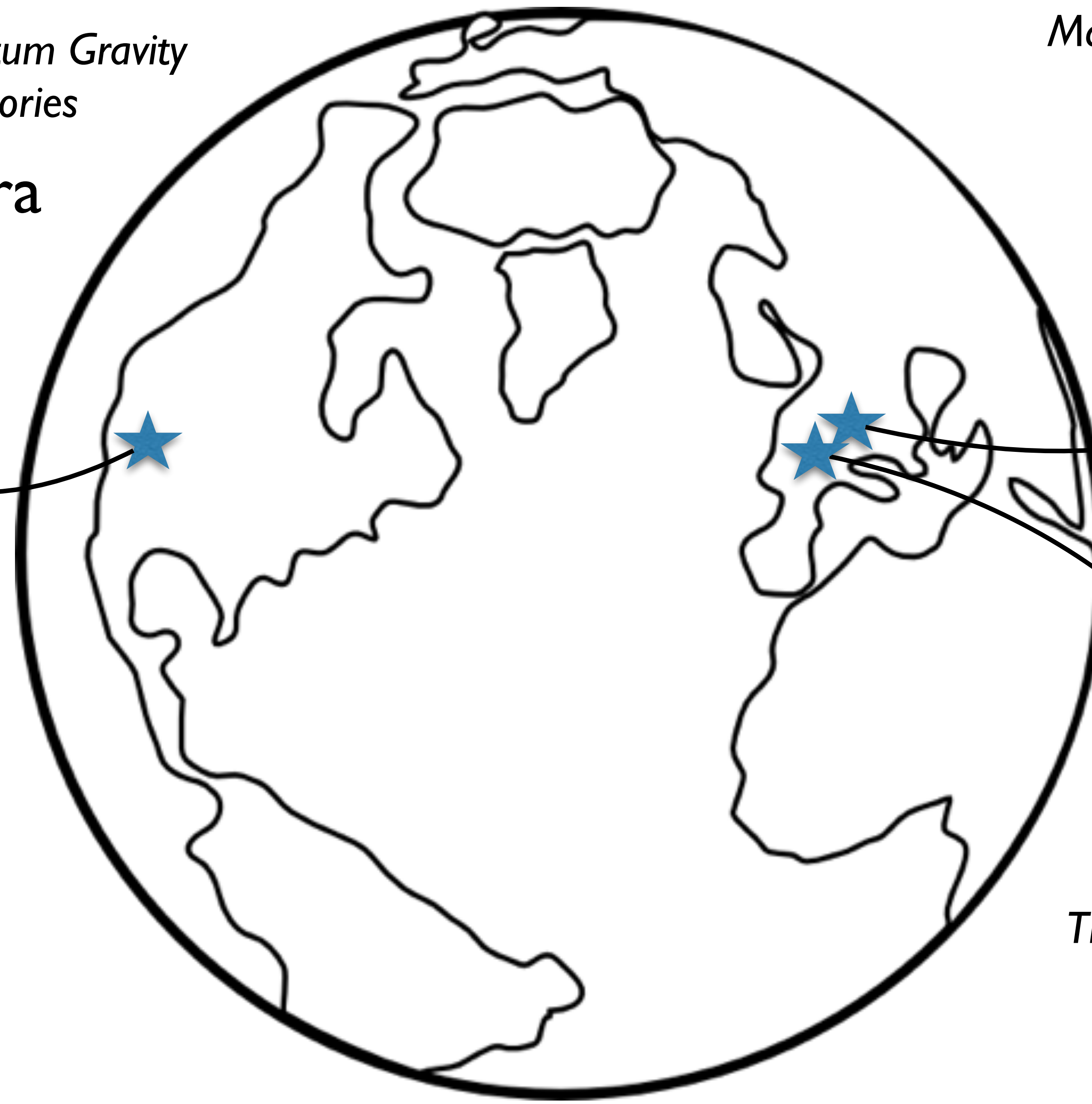
KITP, Santa Barbara

Feb-Mar 2020

Mathematical Foundations of the Swampland Program

MITP, Mainz

Ago-Sept 2020



The Landscape vs the Swampland

ESI, Vienna

June 2021

Thank you!

back-up slides

	Weak Gravity Conjecture	Swampland Distance Conjecture
Global symmetry restored if	$g \to 0$	$\Delta\phi \to \infty$
Spectra ("electric version")	One? (Sub)Lattice? Tower?	Infinite tower
	$\frac{Q}{m} \geq 1$ (convex hull)	$g^{ij} \frac{\partial_{\phi_i} m \partial_{\phi_j} m}{m^2} \geq \mathcal{O}(1)$
Cut-off ("magnetic version")	$\Lambda < g M_p$	$\Lambda \sim M_p \exp(-\lambda \Delta\phi)$ $\lambda \sim \mathcal{O}(1)$?

	Weak Gravity Conjecture	Swampland Distance Conjecture
Global symmetry restored if	$g \to 0$	$\Delta\phi \to \infty$
Spectra ("electric version")	One? (Sub)Lattice? Tower?	Infinite tower
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Cut-off ("magnetic version")	$\Lambda < g M_p$	$\Lambda \sim M_p \exp(-\lambda\Delta\phi)$ $\lambda \sim \mathcal{O}(1)$?

global symmetry

$\downarrow \; \uparrow$?

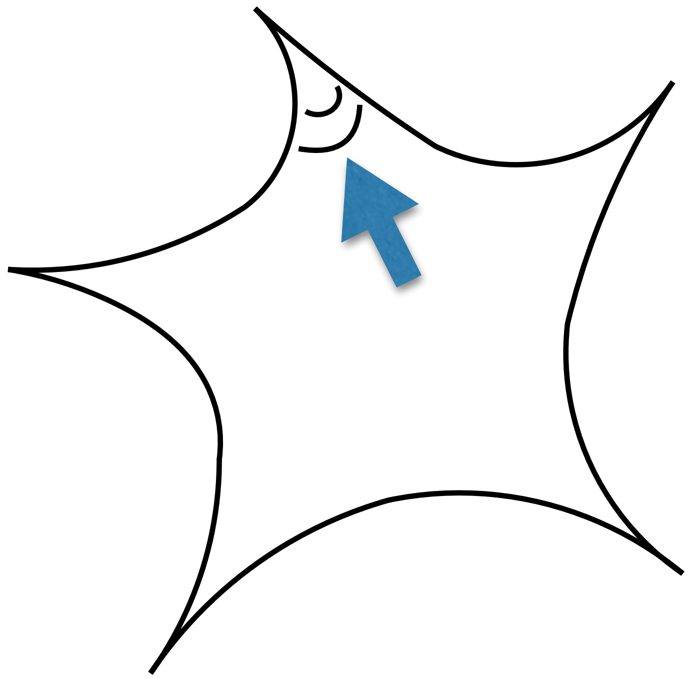
infinite distance

	Weak Gravity Conjecture	Swampland Distance Conjecture
Global symmetry restored if	$g \to 0$	$\Delta\phi \to \infty$
Spectra ("electric version")	One? (Sub)Lattice? Tower?	Infinite tower
	$\frac{Q}{m} \geq 1$ (convex hull)	$g^{ij}\frac{\partial_{\phi_i} m \partial_{\phi_j} m}{m^2} \geq \mathcal{O}(1)$
Cut-off ("magnetic version")	$\Lambda < g M_p$	$\Lambda \sim M_p \exp(-\lambda\Delta\phi)$ $\lambda \sim \mathcal{O}(1)$?

Black hole argument missing

	Weak Gravity Conjecture	Swampland Distance Conjecture
Global symmetry restored if	$g \to 0$	$\Delta\phi \to \infty$
Spectra ("electric version")	One? (Sub)Lattice? Tower?	Infinite tower
	$\frac{Q}{m} \geq 1$ (convex hull)	$g^{ij} \frac{\partial_{\phi_i} m \partial_{\phi_j} m}{m^2} \geq \mathcal{O}(1)$
Cut-off ("magnetic version")	$\Lambda < g M_p$	$\Lambda \sim M_p \exp(-\lambda \Delta\phi)$ $\lambda \sim \mathcal{O}(1)$?
	More than one U(1)?	More than one scalar field? (different trajectories? mixing with axions?)

Physics at infinite field distance

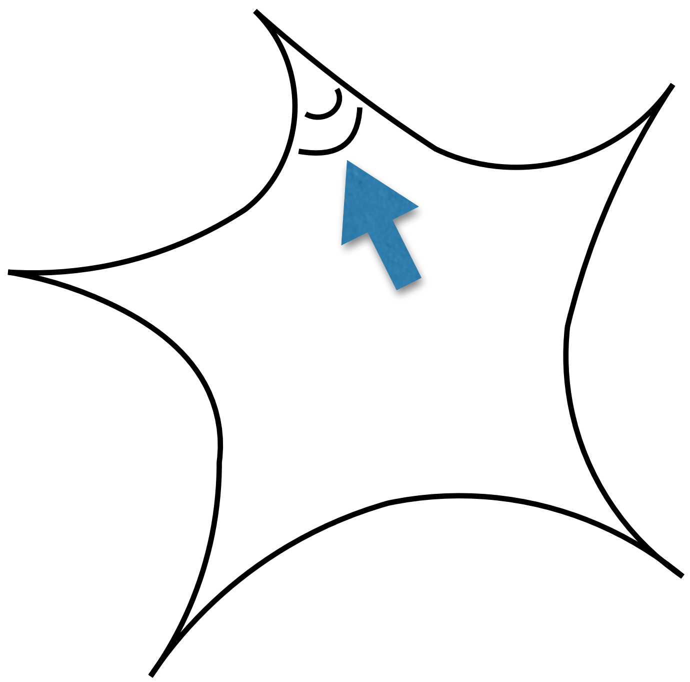


Why interesting?

Einstein gravity, weak gauge theories, axions, large field ranges, approximate global symmetries…

…come at a price

Physics at infinite field distance



Why interesting?

Einstein gravity, weak gauge theories, axions, large field ranges, approximate global symmetries…

…come at a price

Geometrical tool → Limiting Mixed Hodge Structure [Schmid,Cattani,Kaplan]

Growth theorem: gives the leading asymptotic growth of hodge norm w.r.t moduli

(behaviour of field metric, gauge coupling, masses, flux potential…)

Model independent! Only depends on properties of infinite distance singularity

Asymptotic limits

in the moduli space of a Calabi-Yau manifold

We can choose local coordinates so that the singularity occurs at:

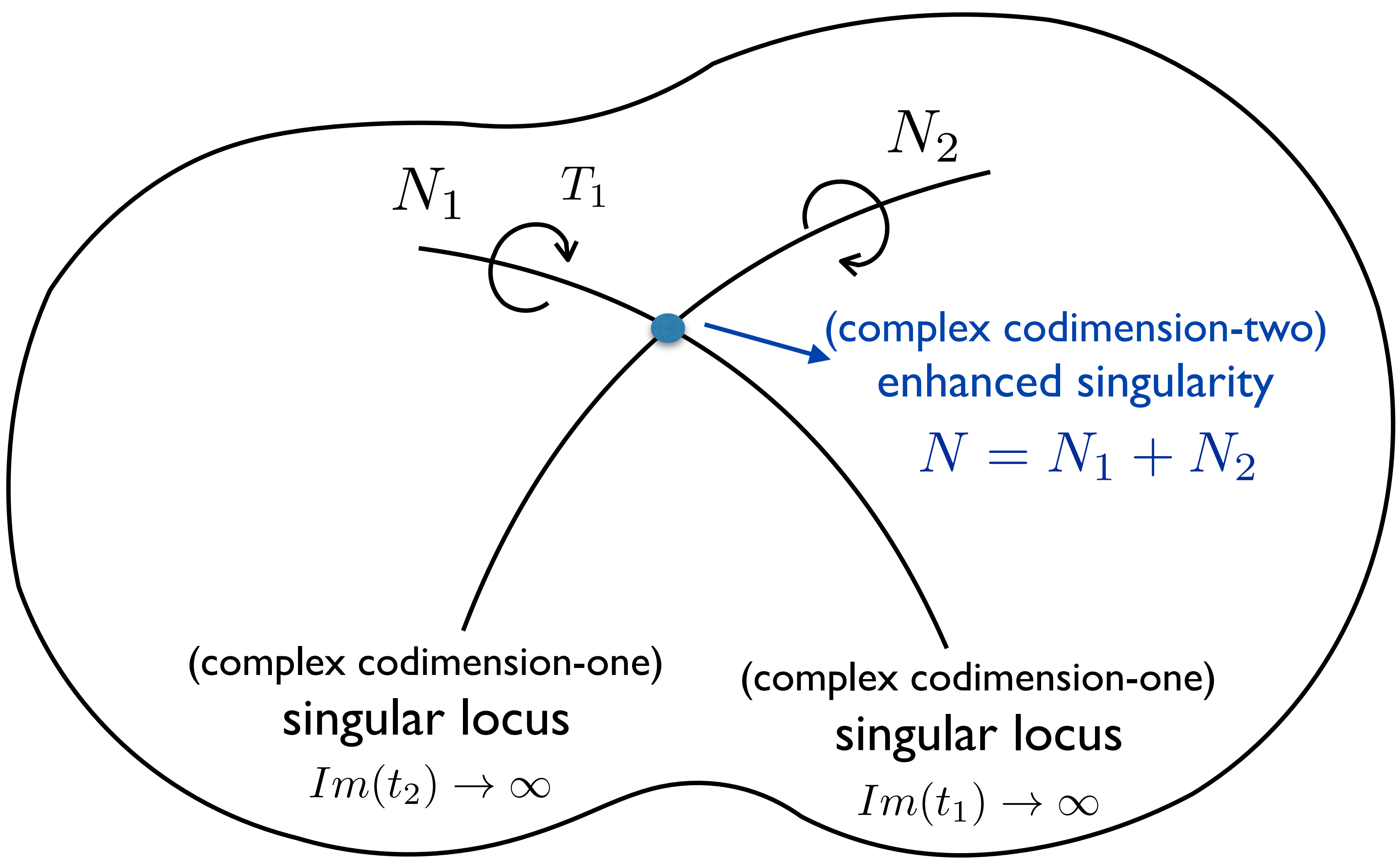
$$t^1, t^2 \rightarrow i\infty$$

where $t^i = \phi^i + is^i$

axion saxion

$$N_i = \log T_i$$

monodromy transformation



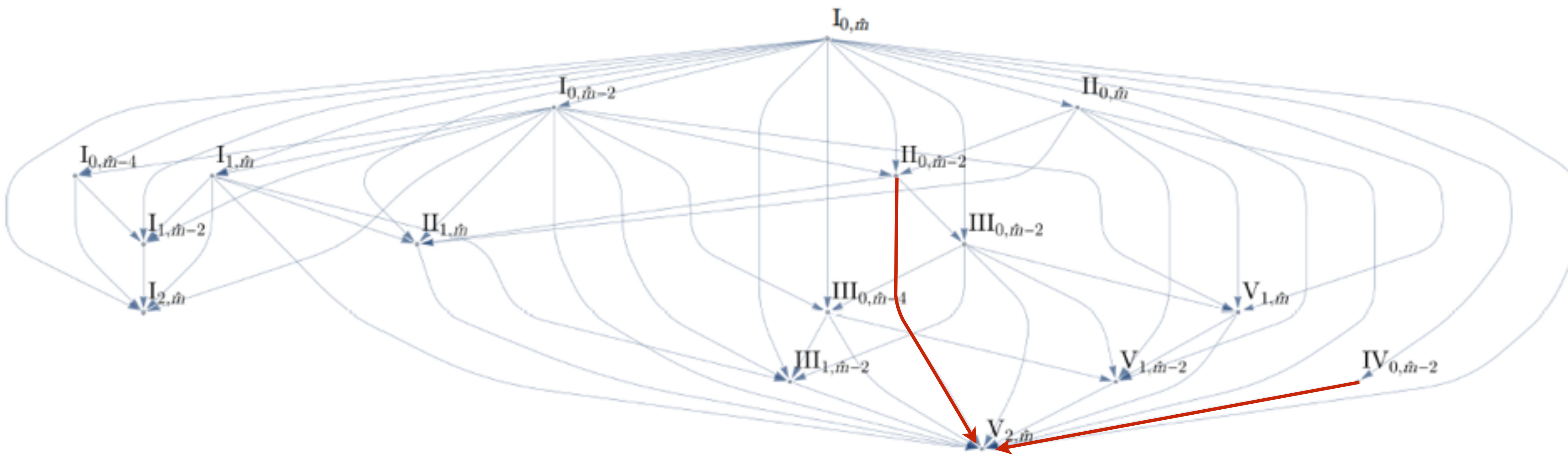
Classification of asymptotic limits

in a Calabi-Yau fourfold

Five main types of singularities: I, II, III, IV, V

infinite distance

[Grimm,Li, IV'19]
[Grimm,Li, Zimmermann]



Asymptotic flux scalar potential

Consider the limit: $t^1, \ldots, t^{\hat{n}} \rightarrow i\infty$, $t^i = \phi^i + is^i$

Given a growth sector $s^1 \gg s^2 \gg \cdots \gg s^{\hat{n}} \gg 1$ we can determine:

[Cattani,Kaplan,Schmid]

I Finer splitting of the cohomology group adapted to the singularity type:

$$H^4_{\mathrm{p}}(Y_4, \mathbb{R}) = \bigoplus_{\boldsymbol{\ell} \in \mathcal{E}} V_{\boldsymbol{\ell}} , \qquad \boldsymbol{\ell} = (\ell_1, \ldots, \ell_{\hat{n}})$$ integer vector

Asymptotic flux splitting: $$\mathbf{G}_4 = \sum_{\boldsymbol{\ell} \in \mathcal{E}} \mathbf{G}_4^{\boldsymbol{\ell}}$$

The flux splits into pairwise orthogonal components:

$$\int_{CY_4} G_4^{\boldsymbol{\ell}} \wedge G_4^{\boldsymbol{\ell}'} = 0 \quad \text{unless} \quad \boldsymbol{\ell} + \boldsymbol{\ell}' = \mathbf{8} \, ,$$

Asymptotic flux scalar potential

Consider the limit: $t^1, \ldots, t^{\hat{n}} \to i\infty$, $t^i = \phi^i + is^i$

Given a growth sector $s^1 \gg s^2 \gg \cdots \gg s^{\hat{n}} \gg 1$ we can determine:

[Cattani,Kaplan,Schmid]

2 Asymptotic leading behaviour of hodge norm: $\int G_4 \wedge *G_4 \sim \sum_{\boldsymbol{\ell} \in \mathcal{E}} \|G_4^{\boldsymbol{\ell}}\|^2_{sl(2)}$

$$\|G_4^{\boldsymbol{\ell}}\|^2_{\mathrm{sl}(2)} = \underbrace{\left(\frac{s^1}{s^2}\right)^{\ell_1 - 4} \cdots \left(\frac{s^{\hat{n}-1}}{s^{\hat{n}}}\right)^{\ell_{\hat{n}-1}-4} (s^{\hat{n}})^{\ell_{\hat{n}}-4}}_{s\,:\ \text{saxions}} \underbrace{\|\rho_{\boldsymbol{\ell}}(G_4, \phi)\|^2_\infty}_{\phi\,:\ \text{axions}}$$

$\rho(G_4, \phi) \equiv e^{\phi^i N_i} G_4$

Strict asymptotic approx.: it drops out terms of $\mathcal{O}(s^{i+1}/s^i)$

Natural interpretation in terms of the potential derived from Minkowski 3-form gauge fields:

[Bielleman,Ibanez,IV,Carta,Marchesano,Staessens,Zoccarato,Farakos,Lanza,Martucci,Sorokin,Herraez,Quirant…'15-19]

Two moduli limits

Enhancements	Potential V_{M}
$\mathrm{I}_{0,\hat m-2},\ \mathrm{V}_{1,\hat m} \rightarrow \mathrm{V}_{1,\hat m-2}$	$\frac{c_1}{s} + \frac{c_2}{u^4} + \frac{c_3}{u^2} + c_4 u^2 + c_5 u^4 + c_6 s - c_0$
$\mathrm{I}_{0,\hat m-2},\ \mathrm{V}_{1,\hat m-2} \rightarrow \mathrm{V}_{2,\hat m}$	$\frac{c_1}{us} + \frac{c_2}{u^4} + \frac{c_3}{u^2} + \frac{c_4 u}{s} + \frac{c_5 s}{u} + c_6 u^2 + c_7 u^4 + c_8 us - c_0$
$\mathrm{I}_{1,\hat m},\ \mathrm{V}_{1,\hat m} \rightarrow \mathrm{V}_{2,\hat m}$	$\frac{c_1}{s^2} + \frac{c_2}{u^4} + \frac{c_3}{u^2} + c_4 u^2 + c_5 u^4 + c_6 s^2 - c_0$
$\mathrm{II}_{0,\hat m-2},\ \mathrm{IV}_{0,\hat m-2} \rightarrow \mathrm{V}_{2,\hat m}$	$\frac{c_1}{u^3 s} + \frac{c_2}{us} + \frac{c_3 u}{s} + \frac{c_4 u^3}{s} + \frac{c_5 s}{u^3} + \frac{c_6 s}{u} + c_7 us + c_8 u^3 s - c_0$
$\mathrm{I}_{0,\hat m-2},\ \mathrm{I}_{0,\hat m-4} \xrightarrow{a} \mathrm{I}_{1,\hat m-2}$ $\mathrm{I}_{0,\hat m-2},\ \mathrm{II}_{0,\hat m-2} \rightarrow \mathrm{II}_{1,\hat m}$	$\frac{c_1}{us} + \frac{c_2}{u} + \frac{c_3 u}{s} + \frac{c_4 s}{u} + c_5 u + c_6 us - c_0$
$\mathrm{I}_{0,\hat m-2},\ \mathrm{I}_{1,\hat m} \xrightarrow{b} \mathrm{I}_{1,\hat m-2}$ $\mathrm{I}_{0,\hat m-2},\ \mathrm{III}_{0,\hat m-2} \rightarrow \mathrm{III}_{0,\hat m-4}$ $\mathrm{I}_{1,\hat m},\ \mathrm{II}_{0,\hat m} \rightarrow \mathrm{II}_{1,\hat m}$	$\frac{c_1}{s} + \frac{c_2}{u^2} + c_3 u^2 + c_4 s - c_0$
$\mathrm{I}_{0,\hat m-2},\ \mathrm{I}_{1,\hat m-2} \rightarrow \mathrm{I}_{2,\hat m}$ $\mathrm{I}_{0,\hat m-2},\ \mathrm{III}_{0,\hat m-4} \rightarrow \mathrm{III}_{1,\hat m-2}$	$\frac{c_1}{us} + \frac{c_2}{u^2} + \frac{c_3 u}{s} + \frac{c_4 s}{u} + c_5 u^2 + c_6 us - c_0$
$\mathrm{I}_{0,\hat m-2} \Rightarrow \mathrm{I}_{0,\hat m-4}$ $\mathrm{I}_{0,\hat m-2} \Rightarrow \mathrm{II}_{0,\hat m-2}$ $\mathrm{II}_{0,\hat m} \Rightarrow \mathrm{II}_{0,\hat m-2}$ $\mathrm{I}_{0,\hat m-2},\ \mathrm{II}_{0,\hat m} \rightarrow \mathrm{II}_{0,\hat m-2}$	$\frac{c_1}{s} + \frac{c_2}{u} + c_3 u + c_4 s - c_0$
$\mathrm{I}_{0,\hat m-2} \Rightarrow \mathrm{I}_{1,\hat m}$ $\mathrm{I}_{0,\hat m-4} \Rightarrow \mathrm{I}_{2,\hat m}$ $\mathrm{II}_{0,\hat m-2} \Rightarrow \mathrm{III}_{0,\hat m-2}$	$\frac{c_1}{us} + \frac{c_2 u}{s} + \frac{c_3 s}{u} + c_4 us - c_0$
$\mathrm{I}_{1,\hat m} \Rightarrow \mathrm{I}_{2,\hat m}$ $\mathrm{I}_{1,\hat m} \Rightarrow \mathrm{III}_{1,\hat m-2}$ $\mathrm{III}_{0,\hat m-2} \Rightarrow \mathrm{III}_{1,\hat m-2}$ $\mathrm{I}_{1,\hat m},\ \mathrm{III}_{0,\hat m-2} \rightarrow \mathrm{III}_{1,\hat m-2}$	$\frac{c_1}{s^2} + \frac{c_2}{u^2} + c_3 u^2 + c_4 s^2 - c_0$
$\mathrm{III}_{1,\hat m-2} \Rightarrow \mathrm{V}_{2,\hat m}$	$\frac{c_1}{u^2 s^2} + \frac{c_2}{s^2} + \frac{c_3}{u^2} + \frac{c_4 u^2}{s^2} + \frac{c_5 s^2}{u^2} + c_6 u^2 + c_7 s^2 + c_8 u^2 s^2 - c_0$

[Grimm,Li, IV'19]

Classification of asymptotic flux-induced scalar potentials!

We compute leading behaviour of the flux induced scalar potential for the 36 possible asymptotic limits

$$s, u \rightarrow \infty$$

Two moduli limits

Enhancements	Potential V_{M}
$\mathrm{I}_{0,\hat{m}-2},\ \mathrm{V}_{1,\hat{m}} \to \mathrm{V}_{1,\hat{m}-2}$	$\frac{c_1}{s}+\frac{c_2}{u^4}+\frac{c_3}{u^2}+c_4u^2+c_5u^4+c_6s-c_0$
$\mathrm{I}_{0,\hat{m}-2},\ \mathrm{V}_{1,\hat{m}-2} \to \mathrm{V}_{2,\hat{m}}$	$\frac{c_1}{us}+\frac{c_2}{u^4}+\frac{c_3}{u^2}+\frac{c_4u}{s}+\frac{c_5s}{u}+c_6u^2+c_7u^4+c_8us-c_0$
$\mathrm{I}_{1,\hat{m}},\ \mathrm{V}_{1,\hat{m}} \to \mathrm{V}_{2,\hat{m}}$	$\frac{c_1}{s^2}+\frac{c_2}{u^4}+\frac{c_3}{u^2}+c_4u^2+c_5u^4+c_6s^2-c_0$
$\mathrm{II}_{0,\hat{m}-2},\ \mathrm{IV}_{0,\hat{m}-2} \to \mathrm{V}_{2,\hat{m}}$	$\frac{c_1}{u^3s}+\frac{c_2}{us}+\frac{c_3u}{s}+\frac{c_4u^3}{s}+\frac{c_5s}{u^3}+\frac{c_6s}{u}+c_7us+c_8u^3s-c_0$
$\mathrm{I}_{0,\hat{m}-2},\ \mathrm{I}_{0,\hat{m}-4} \to \mathrm{I}_{1,\hat{m}-2}$	$\frac{c_1}{us}+\frac{c_2}{u}+\frac{c_3u}{s}+\frac{c_4s}{u}+c_5u+c_6us-c_0$
$\mathrm{I}_{0,\hat{m}-2},\ \mathrm{II}_{0,\hat{m}-2} \to \mathrm{II}_{1,\hat{m}}$	
$\mathrm{I}_{0,\hat{m}-2},\ \mathrm{I}_{1,\hat{m}} \to \mathrm{I}_{1,\hat{m}-2}$	$\frac{c_1}{s}+\frac{c_2}{u^2}+c_3u^2+c_4s-c_0$
$\mathrm{I}_{0,\hat{m}-2},\ \mathrm{III}_{0,\hat{m}-2} \to \mathrm{III}_{0,\hat{m}-4}$	
$\mathrm{I}_{1,\hat{m}},\ \mathrm{II}_{0,\hat{m}} \to \mathrm{II}_{1,\hat{m}}$	
$\mathrm{I}_{0,\hat{m}-2},\ \mathrm{I}_{1,\hat{m}-2} \to \mathrm{I}_{2,\hat{m}}$	$\frac{c_1}{us}+\frac{c_2}{u^2}+\frac{c_3u}{s}+\frac{c_4s}{u}+c_5u^2+c_6us-c_0$
$\mathrm{I}_{0,\hat{m}-2},\ \mathrm{III}_{0,\hat{m}-4} \to \mathrm{III}_{1,\hat{m}-2}$	
$\mathrm{I}_{0,\hat{m}-2} \Rightarrow \mathrm{I}_{0,\hat{m}-4}$	$\frac{c_1}{s}+\frac{c_2}{u}+c_3u+c_4s-c_0$
$\mathrm{I}_{0,\hat{m}-2} \Rightarrow \mathrm{II}_{0,\hat{m}-2}$	
$\mathrm{II}_{0,\hat{m}} \Rightarrow \mathrm{II}_{0,\hat{m}-2}$	
$\mathrm{I}_{0,\hat{m}-2},\ \mathrm{II}_{0,\hat{m}} \to \mathrm{II}_{0,\hat{m}-2}$	
$\mathrm{I}_{0,\hat{m}-2} \Rightarrow \mathrm{I}_{1,\hat{m}}$	$\frac{c_1}{us}+\frac{c_2u}{s}+\frac{c_3s}{u}+c_4us-c_0$
$\mathrm{I}_{0,\hat{m}-4} \Rightarrow \mathrm{I}_{2,\hat{m}}$	
$\mathrm{II}_{0,\hat{m}-2} \Rightarrow \mathrm{III}_{0,\hat{m}-2}$	
$\mathrm{I}_{1,\hat{m}} \Rightarrow \mathrm{I}_{2,\hat{m}}$	$\frac{c_1}{s^2}+\frac{c_2}{u^2}+c_3u^2+c_4s^2-c_0$
$\mathrm{I}_{1,\hat{m}} \Rightarrow \mathrm{III}_{1,\hat{m}-2}$	
$\mathrm{III}_{0,\hat{m}-2} \Rightarrow \mathrm{III}_{1,\hat{m}-2}$	
$\mathrm{I}_{1,\hat{m}},\ \mathrm{III}_{0,\hat{m}-2} \to \mathrm{III}_{1,\hat{m}-2}$	
$\mathrm{III}_{1,\hat{m}-2} \Rightarrow \mathrm{V}_{2,\hat{m}}$	$\frac{c_1}{u^2s^2}+\frac{c_2}{s^2}+\frac{c_3}{u^2}+\frac{c_4u^2}{s^2}+\frac{c_5s^2}{u^2}+c_6u^2+c_7s^2+c_8u^2s^2-c_0$

[Grimm,Li, IV'19]

Classification of asymptotic flux-induced scalar potentials!

We compute leading behaviour of the flux induced scalar potential for the 36 possible asymptotic limits

$$s, u \to \infty$$

weak coupling + large volume limit in IIA

$$V_{\mathrm{M}} \sim \frac{1}{\mathcal{V}_4^3}\left(\sum_{p=0,2,4,6}\frac{A_{f_p}}{u^{p-3}s}+\sum_{q=0,1,2,3}\frac{A_{h_q}s}{u^{3-2q}}-A_{\mathrm{loc}}\right)$$

$s \to \infty$ (type II): weak coupling

$u \to \infty$ (type IV): large volume

Other results

There are AdS vacua at parametric control if we include:

$$G_4 = \hat{G}_4 + G_4^0$$

unbounded massless fluxes: $\langle \hat{G}_4, \hat{G}_4 \rangle = 0 \ , \quad \langle \hat{G}_4, G_4^0 \rangle = 0$

$\|\hat{G}_4\| \to 0$ as $s, u \to \infty$

Only scale separation at weak coupling/LCS point

[DeWolfe,Giryavets,Kachru,Taylor'05]

Geometric origin of universal backreaction when displacing the axions

$$V(\beta s^i, \beta \phi^i) \simeq \beta^{d_i} V(s^i, \phi^i)$$

$$\partial_{s^i} V = 0 \to s^i = \lambda\, \phi^i + \dots$$

Consistent with Refined SDC

[Ooguri-Vafa'06] [Klaewer,Palti'16]

Phenomenological implications

- Upper bound on the scalar field range that can be described by an effective field theory with finite cut-off
  - **Large field inflation**
  - **Cosmological relaxation of the EW scale**

$$\Delta\phi \lesssim \frac{1}{\lambda}\log\left(\frac{M_p}{\Lambda}\right)$$

What is λ ?

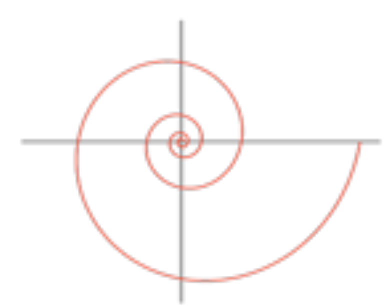
λ is related to the properties of the discrete infinite symmetry generating the orbit of states

- One parameter moduli spaces: $\boxed{\lambda = \sqrt{d}}$ $\left(N^d a_0 \neq 0\ ,\ N^{d+1}a_0 = 0\right)$ order one factor!

- Beyond geodesics:

Multiple saxions: $\lambda\uparrow,\ \Delta\phi\downarrow$

Axionic trajectory: $\lambda\downarrow,\ \Delta\phi\uparrow$



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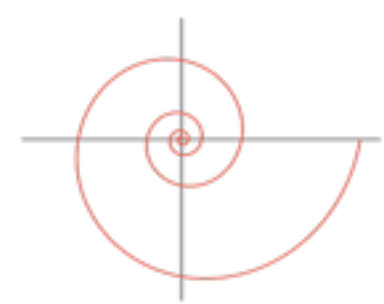

What type of trajectories are allowed by the asymptotic scalar potential arising at infinite distance?